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Metal Production in Quasars through Jet-Gas Interactions

Dissertation

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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ABSTRACT

Emission lines studies of the gas surrounding many high redshift quasars indicate a high concentration of CNO nuclides. Relative abundance ratios may even exceed solar levels in some objects with redshifts near 5.0, indicating a rapid buildup of metals within one billion years after the big bang. Models explaining these high concentrations through standard stellar processing are pressed by the short time requirement.

We explore a non-stellar nucleosynthesis mechanism in quasars based on the interaction of a high energy particle jet with hot, relatively dense gas. Although temperatures in the hot gas are high enough to support (thermalized) thermonuclear reactions, this mechanism alone is too slow to allow a rapid buildup of CNO nuclides. The collision of (non-thermal) jet particles with gas particles allows creation of unique nuclides which can boost the nucleosynthesis over traditional mass gaps at $A=5$ and $A=8$.

The temperature and initial particle density range from $T_g=0.2$ to $T_g=5.0$, and $10^{11}$ to $10^{18}$ particles/cm$^3$, respectively, while the jet intensity varies from 0.1 to 10 solar masses per year. The maximum final density allowed is $10^{23}$ particles/cm$^3$. Substantial metal production in just 100 days can occur for temperatures near $T_g=0.6$. 

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and final densities of $10^{21}$ particles/cm$^3$. Production at other temperatures and densities varies greatly. If the temperature is much above or below $T_9 = 0.6$, or if the density cannot reach $10^{21}$ particles/cm$^3$, then metal production is limited.

Although the simple jet-clump model by itself does not seem capable of fully explaining the solar abundances in quasar gas, the low level production occurs on sufficiently short time scales so that it is still interesting. Also, a simplistic exploration of the production resulting from gas which evolves from high to low temperatures seems to indicate that at least $1/100$th of solar levels can be obtained if the density can climb to $10^{21}$ particles/cm$^3$ in a single processing episode of about 200 days. Multiple processing episodes and more complicated cooling scenarios may indicate larger nucleosynthesis possibilities. Therefore, the jet-clump model offers an exciting possibility for generating metals in quasars.
To Sharon, who made me finish this thing.
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Without the support of many others, this project would not have been possible to do, nor desirable to attempt. I would like to thank my advisor, Dr. Richard Boyd, for his role in providing the interesting ideas which launched this research over two years ago. I am glad that he directed me to work on this particular problem, and I am thankful for his encouragement and support along the way. Dr. Gerhard Raimann assisted me in working through the details involved in many of the ideas presented here. Also, he labored over the first draft and provided many helpful comments. Of course, Sharon, my wife, deserves at least half the credit for this work, since she exerted so much effort in keeping me motivated during the difficult times. My parents, too, have given me a great deal of support by believing in me for as long as I can remember. Finally, I am grateful to God for giving me the chance to explore this wonderful universe in which we live.
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CHAPTER 1

Quasar Properties

In order to provide a backdrop to the discussion of our model for generating metal abundances in quasars, we first give a brief tour of quasar history and structure.

1.1 Historical Introduction

Quasars were discovered first at radio wavelengths by sky surveys done in the late 1950's. Although the angular resolution of these surveys was not precise by today's standards, astronomers were able to find optical counterparts for some of the radio sources. The images resembled star-like point sources, but showed extra distortion around the edges (see Figure 1.1). The name quasi-stellar radio source, later shortened to quasar, reflects the initial consternation raised by the observations. Although the optical image appeared similar to that of a fuzzy star, the spectrum of a typical quasar presented unidentified emission lines at bizarre wavelengths and thus was different from any known stellar spectrum. The true nature of quasars began to unfold in 1963 when Maarten Schmidt was able to identify the strange lines in the spectrum of 3C 273 as hydrogen Balmer emission lines at an extremely high redshift (Schmidt 1963).
This redshift was a factor of ten higher than redshifts of other galaxies under study at the time and was the key to unlocking a series of remarkable revelations about quasars.

1.2 Basic Properties

In fact, almost every basic property of quasars represents an extreme. Large redshifts imply that the distance to quasars is of cosmological proportions. Many quasars are now known with redshifts well above 4. For \( \Omega_0 = 1.0 \) and \( H_0 = 60 \) km/sec/Mpc (see definitions below), a redshift of 4.0 corresponds to lookback times
on the order of 9.9 Gyr, a sizeable fraction of the age of the universe, which is 10.9 Gyr for this $\Omega_0$ and $H_0$.

Calculating lookback times (the light transit time from the object to us) to such highly redshifted objects requires knowledge of cosmological parameters which characterize how the universe has been expanding (Kolb & Turner 1990). Often used for this purpose are $H_0$, the current expansion rate in units of km/sec/Mpc (estimated range is from 50 to 100) and $q_0$, a dimensionless quantity called the deceleration parameter which specifies the rate at which the expansion is slowing down (estimated range is from a minimum of about 0.15 to an upper limit of 0.5). However, rather than use $q_0$, we reference a particular cosmology by $\Omega_0$, which is simply related to $q_0$ by $\Omega_0 = 2q_0$ and represents the ratio of the density of the universe to its critical density (the density which would cause the expansion rate of the universe to approach zero only at infinite time).

The mere fact that quasars are observable at such great distances indicates that they must also have extreme luminosities. Based on the flux at the earth and the estimated distance to the source, a typical quasar will emit up to $10^{17}$ ergs/sec (Netzer 1990), which is several orders of magnitude more energy output than the optical luminosity of a large galaxy. It is true that some supernovae will emit up to $10^{51}$ ergs/sec for a few seconds (Burrows 1990), but quasars last for at least $10^8$ years, making them the most energetic objects in the universe.

Since individual quasars emit much more light than an entire galaxy, one might expect quasars to be enormous objects. Yet the brightness of many quasars can vary
significantly on time scales as short as one day, constraining the size to a surprisingly small upper limit of one light day. For comparison, the solar system is about one-half light day in diameter, and the Milky Way is about 50 million light days across. Somehow, the equivalent output of 100 galaxies must be blasting out of a region roughly the diameter of our solar system!

Over the past thirty years, various phenomena have been postulated to explain fundamental quasar observations. Initially, astronomers wondered if the redshifts truly implied cosmological distances, or if quasars were local objects which somehow merely appeared to be receding (Burbidge & Burbidge 1967). Since no plausible mechanism was found to account for nearby objects with large redshifts, this hypothesis was discarded. With quasars firmly established as cosmologically remote, the problem shifted to explaining the luminosity, which, due to the rapid variability, must originate in a relatively small volume, independent of the distance to the quasar. Some very interesting schemes for generating large amounts of energy per volume were proposed (Burbidge & Burbidge 1967), including large scale annihilations of matter and anti-matter, conversion of bare quarks (left over from the big bang) to baryons and mesons, collisions of and supernovae of massive stars, and gravitational focusing of distant galaxies.

However, as the characteristics of quasars have been refined observationally, only one model has survived serious scrutiny.

Much of the evidence implicates black holes as the power source behind all quasars. In this scenario, a supermassive black hole of $10^6$ to $10^9$ $M_\odot$ sitting at the center of a
host galaxy draws in matter from its host, and as this matter falls into the potential well of the black hole, it is heated to high temperatures. Viscous forces convert the potential energy of the infalling matter into thermal energy. For a mass $m$ falling into a $10^8 M_\odot$ black hole, the thermal energy can be as high as $0.1 \: mc^2$, i.e., 10% of its rest mass. In comparison, nuclear fission of $^1$H to $^4$He only releases 0.007% of the $^4$He mass as energy (Peterson 1997). If a sizable fraction of the thermal energy is converted to outgoing radiation, then the luminosity requirement of quasars can be easily met by the black hole model.

The black hole and the hot, inner region with its accompanying continuum emission are collectively referred to as the central engine of the quasar. Understanding the specific processes by which the black hole generates the continuum is a complex topic closely tied to the accretion details which we do not summarize, but which the interested reader may explore in the literature (Peterson 1997; Blandford 1990).

Also, simple arguments can show that the size of a massive black hole is consistent with the known compactness of quasars. The size of a black hole is characterized by the Schwarzschild radius, $R_S$, also called the event horizon, below which no matter or even photons can return from their descent into the black hole. For a non-rotating black hole, $R_S$ is given by

$$R_S = \frac{2GM}{c^2} = 3 \times 10^{12} \frac{M}{M_\odot} \text{ cm} = 10^{-3} \frac{M}{M_\odot} \text{ light-days.} \quad (1.1)$$

where $M$ is the black hole mass in solar masses and $M_\odot$ is $10^7 M_\odot$. Since the last stable orbit around a black hole is at $3R_S$, most of the continuum emission would
occur just beyond this radius (Peterson 1997), which is easily small enough to satisfy the time variability constraint.

The black hole scenario also helps to explain another commonly observed feature of quasars – the appearance of jets of material streaming away from the central region. Also observed on a smaller scale in star formation, particle jets are thought to be the consequence of accretion onto a centrally located massive object. Many accretion scenarios favor the formation of an accretion disk through which matter passes as it spirals into the black hole. Along the axis of the disk, material is somehow propelled outward in the jet, which shoots away from either side of the disk.

Our model depends on the presence of the particle jet, but not on the mechanism by which it is created. Therefore we do not discuss the complex physics describing accretion processes and jet creation mechanisms. Gas characteristics and jet properties required by our model are discussed further in Chapter 3.

1.3 Quasars as Active Galactic Nuclei

Quasars fall into the larger category of objects known as AGNs (the plural of Active Galactic Nucleus). The largest division of AGNs consists of objects known as Seyfert galaxies. These were discovered first, because most are relatively nearby and hence have fairly high apparent luminosities. Nuclei of Seyfert galaxies have a lower intrinsic luminosity compared to quasars, but the two have spectra which are in general very similar. The host galaxy itself can usually be resolved, and practically all Seyferts exhibit a spiral morphology. Seyferts are divided into two groups based on the spectral
width of certain permitted emission lines \(^1\). Type 1 Seyferts show both broad and narrow components in their permitted lines, while type 2 Seyferts have only the narrow component.

Quasars are distinguished by their higher luminosity, with the boundary between Seyferts and quasars set by historical factors (Schmidt & Green 1983). The starlight of a quasar’s galactic host is distinguishable only as a halo of fuzz around the quasar, although recently some progress has been made in isolating the halo emission (Bahcall, Kirhakos, & Schneider 1996), which does resemble a possible host galaxy. Luminosity at radio wavelengths is used to divide quasars into two groups, because, unlike the first population of quasars found in the 60’s, most quasars are not strong radio emitters.

Optical surveys (see Sandage 1965) were the first to uncover these so-called “radio-quiet” quasars, whose limited radio emission caused them to be overlooked in the initial surveys. Actually, the overall quasar population is dominated by the radio-quiet objects, and the radio-loud category accounts for only about 10 to 15% of the total (Peterson 1997).

The creation of distinct classes for Seyferts and quasars (Weedman 1976) arose primarily because the first Seyferts observed were at low redshift and had nuclei with relatively low intrinsic luminosities, while the first quasars discovered were further away and quite luminous. 3C 273, the quasar used by Schmidt to solve the highly

---

\(^1\)Emission lines are broadly classified into three categories based on the rate of the atomic transition responsible for the emission. Certain transitions are “forbidden” by atomic selection rules, and therefore the rates at which electrons jump from one such state to another is relatively slow. Permitted transitions are allowed by the selection rules, and thus happen relatively quickly. Intercombination emission lines are generated by transitions with probabilities between those of the forbidden and the permitted transfers.
redshifted emission line puzzle, remains the brightest quasar found to date. Recent
observations have closed the gap between the two groups, so that the luminosity and
redshift boundaries now seem somewhat artificial. This present work is concerned
with the buildup of large metal abundances in objects with the greatest age, and thus
we focus on quasars.

Another group of AGNs is the blazars, which are distinctive primarily in their
rapid variability. Some blazars undergo significant changes in luminosity over times as
short as one day, and a significant fraction of their radiation is polarized (Miller 1989).
The polarized radiation fluctuates rapidly in time and often exhibits superluminal
motion, where portions of the object seem to move across the sky at speeds greater
than the speed of light. Some of these characteristics can be explained if blazars
are AGNs viewed down the axis of the jet, whose relativistically beamed particles
can exhibit apparent transverse velocities greater than the speed of light (Blandford,
McKee, & Rees 1977). All blazars are radio loud objects.

Besides Seyferts, quasars, and blazars, other types of AGNs exist but our focus
is quasars, and we do not provide details for these other groups.

One major thrust of AGN research is to explain the diverse observations for all
classes of AGNs with a single underlying physical model. The blurred boundaries
between quasars and Seyfert galaxies seem to suggest that is possible.

Most unification schemes rely on the fact that the radiation from quasars is not
isotropic, as would be expected for a flattened accretion disk with bipolar jets. The
angle at which the system is viewed will then have a significant impact on the classification of such objects. Blandford (1990) and Peterson (1997) provide more details on some unification schemes.
1.4 Regions of Quasar Emission

Figure 1.2 shows a typical quasar spectrum. The underlying continuum emission comes from the central engine, and the total continuum energy can be explained by the black hole model. Broad features in the spectrum can be reproduced by several varieties of accretion scenarios. Unfortunately, the plethora of free parameters in accretion models has prevented any one model from standing out as a unique fit to the observations. Reprocessing of outgoing radiation by hot or cold material in the central engine may also be invoked to explain some qualitative features of the spectrum.

The remaining features, the emission lines, originate at radii beyond the central engine. Some lines have both broad and narrow components which can vary independently over time, and thus the broad and narrow emission must occur in separate regions with different physical properties. These two regions are called the Broad Line Region (BLR) and the Narrow Line Region (NLR).

The BLR lies closest to the continuum source. Any changes in the continuum radiation are closely followed by changes in the line strengths, clearly identifying the continuum as source of ionizing radiation for the BLR (Clavel et al. 1991; Peterson et al. 1991). Key BLR properties are shown in Table 1.4. Some of these quantities are known only approximately. The temperature, for example, is difficult to determine.
Table 1.1: Selected properties of the regions responsible for broad and narrow line emission in AGNs. Data are summarized from various chapters in Peterson (1990).

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value in BLR</th>
<th>Value in NLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Width</td>
<td>500 to $10^4$ km/s FWHM</td>
<td>200 to 900 km/s FWHM</td>
</tr>
<tr>
<td>Temperature</td>
<td>roughly $10^4$ K</td>
<td>1.0 to $2.5 \times 10^4$ K</td>
</tr>
<tr>
<td>Electron Density</td>
<td>$10^8$ to $10^{11}$ cm$^{-3}$</td>
<td>$10^2$ to $10^4$ cm$^{-3}$</td>
</tr>
<tr>
<td>Total Mass</td>
<td>10 $M_\odot$</td>
<td>100 to 1000 $M_\odot$</td>
</tr>
<tr>
<td>Number of Clouds</td>
<td>$10^5$</td>
<td>$\leq 10^5$</td>
</tr>
<tr>
<td>Average Cloud Size</td>
<td>400 solar radii</td>
<td>0.1 light yr</td>
</tr>
<tr>
<td>Covering Factor</td>
<td>0.1</td>
<td>unknown due to dust</td>
</tr>
<tr>
<td>Total Size</td>
<td>10 light day</td>
<td>300 light yr</td>
</tr>
</tbody>
</table>

at BLR densities, where the lines typically used as temperature diagnostics are collisionally suppressed\(^2\). At temperatures of $10^4$ K, the thermal velocity width is only 10 km/s, which indicates that most of the line width comes from the relative motion of separate clouds within the BLR. With no features of individual clouds visible in even the highest resolution spectra, there must be a large number of clouds in the BLR (Atwood, Baldwin, & Carswell 1982; Capriotti, Foltz, & Byard 1981).

Instabilities to thermal evaporation (Matthews & Capriotti 1985) require that BLR clouds be constrained by some mechanism other than gravity. The Jeans mass (the minimum mass needed for an object to collapse under its own gravity) for a gas at $10^4$ K is 100 $M_\odot$, and the total mass of line emitting gas in the BLR is only about

\(^2\)Line emission can be suppressed in high density gas if the transition rate for the atomic electron to decay from a higher state to a lower state is much slower than the rate for collisional de-excitation, which does produce any emergent radiation.
10 M\(_\odot\). Magnetic fields are one possibility (Rees 1987), but no definitive solution exists for this problem.

The NLR lies further from the central engine than the BLR and has lower gas densities. Line emission is less efficient at typical NLR densities, but the NLR has a greater spatial extent and total mass than the BLR, and so each region generates roughly equal amounts of flux to the spectrum. Table 1.4 also lists typical NLR characteristics. It is interesting to note that in some Seyfert galaxies, the NLR can actually be resolved in the optical, making it a powerful probe of AGN models.

Nucleosynthesis in our model (see Chapter 3 for full details) requires temperatures and densities well above those observed in both the BLR and the NLR. Thus we are primarily interested in the emission line regions as general indicators of metal abundances. The task of interpreting the emission spectra in order to extract abundance information is a non-trivial one. The next chapter presents results from some inquiries into quasar abundances.
The total count of known quasars is of order $10^4$ (Hewitt & Burbidge 1993), and high quality spectra are available for many of these objects, even some high redshift ones (Storrie-Lombardi et al. 1996). These spectra contain a wealth of information about the history and evolution of the universe out to redshifts approaching 5.0. Particularly interesting are the prominent metal emission lines visible in nearly all the highest redshift objects. These emission lines hint at the presence of significant metal concentrations, which, since metals are not thought to have been produced in the big bang, would then require some type of rapid, early processing of the gas surrounding most quasars' cores.

In this chapter, we first provide a brief reminder of the short time scale for metal production implied by the quasar abundances. Next, we describe the modeling process by which abundance information is extracted from the emission line strengths and highlight some uncertainties encountered in emission line models. The results of several abundance inquiries are summarized. Finally, we comment on the adequacy of current approaches used to understand metal generation in quasars and provide some motivation for our exploration of an alternative model.
2.1 Significance of Metals at High Redshift

Spectra of all quasars show surprisingly strong metal emission lines. All objects in the Storrie-Lombardi et al. (1996) survey of redshift \( z \geq 4 \) quasars show lines for C, N, and O (hereafter referred to as CNO). Analysis of similar spectra (see the next section for more about this process) reveals that the typical CNO concentrations in high redshift objects may be significantly higher than the concentrations found in our own sun, an object which formed billions of years later than \( z = 4 \) quasars. Explaining a plethora of metals becomes increasingly difficult for quasars of higher and higher redshift, because as the redshift increases, the time window for metal production shrinks. The light from a redshift \( z = 4.5 \) quasar began its earthward journey 10.0 Gyr ago, while the current age of the universe is just 10.9 Gyr (both ages assume \( H_0=60 \) and \( \Omega_0 = 1.0 \)), leaving just under 1 Gyr for this object to create its currently observed metal concentrations. Adjusting the cosmological parameters can stretch the window to 1.3 Gyr. This is still a severe time constraint which must be met by any model attempting to explain the abundances in quasars.

\(^1\)Metals to astronomers are all elements heavier than helium. Our model will focus on reproducing the abundances of the metals carbon, nitrogen, and oxygen (CNO).
2.2 Modeling the Emission Line Gas

The question is a simple one: "Given a known amount of line emission from a particular atomic species, what is the concentration of that atom in the emitting gas?" The answer, however, turns out to be incredibly complex. Determining atomic concentrations from an emission line spectrum involves complicated modeling since many parameters other than the concentrations are needed in order to correlate line strengths with abundance information. Furthermore, isolated line strengths are not sensitive to individual atomic abundances due to the dependence of one species' emission on the presence and concentration of other species. However, the dependencies can be used to construct line strength ratios which are related to relative abundances. In simpler models, some line ratios can be constructed which are independent of many physical unknowns. Thus ratios of these lines are not very sensitive to ill-constrained parameters of the gas. Unfortunately, few such lines are visible in AGN spectra.

Models for quasar emission lines focus on the gas in the BLR. That the atoms in BLR gas are ionized by the centrally spawned continuum radiation is firmly established by observations which reveal tight correlations between changes in the continuum strength and changes in emission line strengths (Korista et al. 1995; Blandford 1990). This discovery decreases the parameter space of emission line models by establishing photoionization, rather than collisional processes, as the primary excitation mechanism.

In order to predict line emission from a cloud of BLR gas, the following parameters are needed:
1. gas temperature

2. gas density

3. column density of the whole cloud

4. spectrum (relative energy distribution) of incident ionizing radiation

5. intensity of incident ionizing radiation at the cloud face

6. abundance of each atomic species in the cloud

As mentioned in Chapter 1, many of these parameters are known with only limited accuracy. The temperature, density, and column density can each be estimated confidently only to within a factor of 10. For the incident radiation, the intensity and energy distribution are usually combined into a single quantity called the ionization parameter $U$. If $Q$ is the total number of emitted photons energetic enough to ionize hydrogen (Peterson 1997),

$$Q = \int_{\nu_{\text{min}}}^{\infty} \frac{L_{\nu}}{h\nu} \, d\nu \quad (\text{where } h\nu_{\text{min}} = 13.6 \text{ eV.}) \quad (2.1)$$

then $U$ is defined as the ratio of $Q$ per volume to the number of hydrogen atoms per volume in the cloud. $L_{\nu}$ is the total energy per frequency interval emitted by the source. Thus any gaps in our knowledge of the spectral energy distribution, $L_{\nu}$, will also cause uncertainty in $U$. Since the BLR clouds are mostly hydrogen, the most crucial portion of the spectrum is for frequencies just above $\nu_{\text{min}}$, where the ionization cross section for photons on hydrogen is the highest. However, this portion

16
of all quasars' spectra is absorbed in our galaxy by the interstellar medium, which is also mostly hydrogen. Thus the shape of the continuum in this region is unknown and must be treated as another free parameter which must be adjusted to fit the observed line emission. Finally, the line emission from a particular species does depend on its concentration in the gas. However, the emission of one species is also affected by the concentration of all other species.

Thus, the original question — how to extract a line abundance from the strength of the line emission — presents an oversimplified view of the situation. The practical question is “How well does a particular set of values for all the cloud's properties (including atomic abundances, temperature, density, etc.) reproduce the observed emission line spectrum?” Usually the modeling process is divided into two tasks. The first task is to employ a plausible enrichment scenario to generate a set of atomic abundances. The typical approach used for metal enrichment is described in Section 2.4 of this chapter. Our model for the enrichment is described in Chapter 3.

The second task in replicating quasar abundances involves a photoionization calculation. The approach often taken is first to use the best estimates for the temperature, density, and column density, as constrained by the most recent observations. Next, the ionization parameter is chosen and adjusted so that it reproduces correct ratios for pairs of lines which depend very strongly on the continuum shape and intensity. The output of the model is then predictions of line ratios (other than those used to help set the continuum) which are sensitive to the abundance of the emitting species.
rather than just dependent on cloud properties. In simpler models (which incorporate fewer emission lines), analytic expressions exist for correlating line strengths to abundances. In more complex models, the abundances of many atomic species are simulated in a computer code, and the result is a complete spectrum of emission lines, from which line ratios can be extracted. Thus, only by modeling the physical processes relevant for each species in the cloud can line ratios be properly correlated with abundance ratios.

One further uncertainty in interpreting the emission lines is that two lines may come from physically separate regions of the gas. If those regions have different parameters (temperature, density, etc.), then the line strength ratios may not accurately reflect abundance ratios. Until recently, it was thought that some fine tuning mechanism existed in quasars to adjust densities and temperatures to preferred values. These preferred conditions would always favor production of certain lines. This then would have explained why many different quasars show the same emission lines, and why even the line strengths are often similar from one quasar to the next. However, it was recently pointed out (Baldwin et al. 1995) that if many clouds are present in a wide variety of conditions, then the region of parameter space suitable for effective generation of all the typical lines will be physically realized somewhere. The addition of spectra from clouds which are uniformly distributed over all possible densities and temperatures can yield the typical quasar spectrum, and thus no fine tuning is needed. However, the danger of using line ratios is evident, since two different lines may not be generated in the same physical location. Current studies use lines which.
due to the similarities of their ionization potentials, are known to originate in regions of similar density and temperature, and thus would be expected to arise in the same physical region.

### 2.3 Quasar Abundance Studies

Before discussing the abundance studies, we first make a few comments about the typical way in which abundances are described. A common standard for elemental abundances is the compilation of solar abundances found in Anders & Grevesse (1989). These measurements come from observations of our own sun and from the analysis of meteorites. Solar ratios for selected combinations of elements are shown in Table 2.1. Abundance ratios are often taken relative to the sun, so that a $C/H$ ratio of 10 times solar would indicate a Carbon to Hydrogen ratio of $3.6 \times 10^{-3}$. Other authors often use a bracket notation in which $[C/H] = \log_{10}(C/H) - \log_{10}(C/H)_{\text{solar}}$, where $C/H$ is

<table>
<thead>
<tr>
<th>Elements Compared</th>
<th>Number Abundance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/H</td>
<td>$3.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>N/H</td>
<td>$1.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>O/H</td>
<td>$8.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>N/C</td>
<td>0.31</td>
</tr>
<tr>
<td>N/O</td>
<td>0.13</td>
</tr>
<tr>
<td>O/C</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Table 2.1: Solar values for common metal abundance ratios taken from Anders & Grevesse (1989).
Table 2.2: Abundance ratios relative to solar values for many different intermediate redshift objects. Recent models also confirm solar or higher abundances in objects with redshifts above 4.0. †The composite spectrum used by Shields (1976) is taken from Chan & Burbidge (1975) and is made up of 220 quasars with redshifts in the range 0.06 to 3.53. ‡The composite spectrum of Gaskell et al. (1981) is derived from the analysis of Davidson & Netzer (1979).

<table>
<thead>
<tr>
<th>Object(s)</th>
<th>Redshift</th>
<th>Metal Ratio</th>
<th>Abun. rel.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q0353–383</td>
<td>1.96</td>
<td>N/C</td>
<td>~ 10</td>
<td>Osmer (1980)</td>
</tr>
<tr>
<td>Q0353–383</td>
<td>1.96</td>
<td>N/O</td>
<td>~ 5</td>
<td>Osmer (1980)</td>
</tr>
<tr>
<td>Q0353–383</td>
<td>1.96</td>
<td>C/H</td>
<td>~ 10</td>
<td>Osmer (1980)</td>
</tr>
<tr>
<td>PHL957</td>
<td>2.69</td>
<td>N/C</td>
<td>5</td>
<td>Shields (1976)</td>
</tr>
<tr>
<td>PKS1756+237</td>
<td>1.72</td>
<td>N/C</td>
<td>3 to 12</td>
<td>Shields (1976)</td>
</tr>
<tr>
<td>Composite†</td>
<td>——</td>
<td>N/C</td>
<td>~ 12</td>
<td>Shields (1976)</td>
</tr>
<tr>
<td>Composite‡</td>
<td>——</td>
<td>N/O</td>
<td>~ 1</td>
<td>Gaskell et al. (1981)</td>
</tr>
<tr>
<td>Composite‡</td>
<td>——</td>
<td>C/H</td>
<td>~ 1</td>
<td>Uomoto (1984)</td>
</tr>
<tr>
<td>Six quasars ~ 2</td>
<td>N/C</td>
<td>~ 1</td>
<td>Uomoto (1984)</td>
<td></td>
</tr>
<tr>
<td>Six quasars ~ 2</td>
<td>O/C</td>
<td>~ 1</td>
<td>Uomoto (1984)</td>
<td></td>
</tr>
</tbody>
</table>

the number abundance ratio of carbon to hydrogen. In this work, we shall refer to an abundance ratio as being a certain multiple or fraction of the same solar ratio.

The first quasar abundance studies (Davidson 1973; Shields 1976; Davidson 1977; Osmer 1980; Gaskell, Shields, & Wampler 1981; Uomoto 1984; Osmer, Porter, & Green 1994) relied exclusively on measured ratios of intercombination lines. These lines were only detected in a few sources, but were attractive as abundance indicators because their intensity ratios are easily related in a model independent way to relative abundances as long as the electron density in the source is no higher than $10^{10}$ cm$^{-3}$, at which point collisional de-excitation destroys the correlation with atomic abundance.
Objects with these lines seemed to have abundance ratios which were typical of gas with a metal content anywhere from 0.5 to 15 times typical solar values. Table 2.2 shows abundance ratio estimates from some of the work in this area.

Unfortunately, those early studies have been called into question by subsequent observations (Ferland et al. 1992) which seem to indicate that the densities can reach \(10^{11}\, \text{cm}^{-3}\). If this is the case, then collisional de-excitation of the intercombination lines would require introduction of environmental factors in the relationship between line strength ratios and abundance ratios. More complex modeling is thus required to determine the abundance ratios more accurately.

Recent analyses of quasar spectra (Hamann & Ferland 1992; Hamann & Ferland 1993; Ferland et al. 1996) use stronger and more commonly observed lines which are not subject to collisional de-excitation even at densities of \(10^{11}\, \text{cm}^{-3}\). Two key abundance ratios in this approach are N/C and N/He, which are obtained from the line strengths of lines N V 1240 Å, C IV 1550 Å, and He II 1640 Å. The Roman numeral \(n\) after the ion species is related to the (positive) charge \(q\) of the ion by \(n = q + 1\). and the Arabic number indicates the wavelength of the particular transition.

The photoionization calculations of Hamann & Ferland (1993) indicate that the N V/C IV and N V/He II ratios from many quasars with redshifts up to 4 can be reproduced only by gas which has a metal content substantially higher than solar levels. Since the models they use for creating the metals (the stellar models discussed in the next section) do not generate abundances which are simple multiples of solar abundances, they refer to the overall metallicity of the gas. Metallicity is defined as
the mass fraction of all atoms other than hydrogen and helium. Only models which achieve metallicities 3 to 10 times solar can fit the observed ratios for the N/C and N/He lines.

Focused analysis by Ferland et al. (1996) of the specific quasar Q0207-398 also shows that no combination of gas parameters with metallicities less than 5 times solar can reproduce the emission lines N V, C IV, O VI, and He II in this redshift 2.81 object. Thus detailed models have confirmed and strengthened the detection of solar or higher abundances in high redshift quasars.

In spite of the uncertainties, it is difficult to escape the conclusion that many quasars, or at least some regions of quasars, have metal abundances which are quite high, possibly exceeding solar levels by a factor of ten.

2.4 Interpreting the Line Ratios

Stellar nucleosynthesis is the mechanism which all previous abundance studies have employed to account for the buildup of metals in quasars. The basic parameters of stellar metal enrichment scenarios are provided in the following brief description.

Stars form as smaller regions within a large quantity of gas collapse under gravity. This process can be crudely modeled by picturing two separate boxes, one with gas and one with stars. The two parameters which describe the star formation process (and hence metal production) are the star formation rate and the initial (stellar) mass function (IMF). The star formation rate is proportional to the amount of gas which is flowing into the star box. The IMF describes the initial mass distribution of stars
formed from the new gas entering the star box. The new stars begin burning and producing metals according to their initial masses. Stellar evolution studies provide information on the metal output of any star, given its initial mass and composition. Some stars lose mass as they age, and this mass goes back into the gas box. Any mass re-entering the gas box is assumed to mix instantly with the rest of the gas, and so the metal concentrations flowing into the star box will reflect this change. Heavy stars burn hotter and more quickly, and end in violent supernova explosions, which send most of their metal enriched material back into the gas box. Lower mass stars burn cooler and slower, and thus they keep their gas in the star box for a long time, preventing it from being recycled into new stars.

Several options exist for speeding up the metal production of a particular model. First, the star formation rate can be increased while the IMF is kept the same. However, a significant amount of gas will eventually be tied up in low mass stars (which burn more slowly), and the buildup of metals will slow down considerably. Increasing the slope of the IMF to favor production of high mass stars alleviates this problem, allowing rapid recycling of gas through short lived, high mass stars. In addition, a cutoff may be introduced into the IMF which prohibits the creation of the slower burning low mass stars. All of these techniques are used in quasar abundance studies in an attempt to meet the time deadline for generating the metals.

While stellar contributions are likely to dominate quasar metal production, it is possible that other processes may also play a role in generating the abundances in the central quasar environment. The stellar models are being pushed to their limits.
by the short time scales required in the largest redshift objects. In the models of Hamann & Ferland (1993), both the star formation rate and the IMF are set to the most extreme values known. Also, processing in their model begins immediately after the big bang. Any extra delay between the big bang and the onset of star formation would require the star formation rate and the initial mass function to take on values which have yet to be observed in any other environment. These considerations do not invalidate their approach, but the fact that all star forming parameters are adjusted in the same direction, and are close to their plausible limits, indicates that this model is being considerably stretched.

Also, there are several features in quasars which could give rise to nucleosynthesis outside of stars. Few places exist in the universe where very high temperature gas contains protons, because stars convert protons to heavier elements in the early, relatively cooler stages of their evolution. Quasars, however, are known to have very high temperatures in the accretion region around the black hole, and there is no reason to suspect that the infalling material has been depleted of protons. Furthermore, the particle jets observed in AGNs can serve as a supply of high energy particles which are then injected into the surrounding gas. As particles from the jet traverse the gas, occasional nuclear collisions between jet and gas nuclei spawn particle transfer reactions (such as $^4\text{He}(\alpha,n)^7\text{Be}$). Products of these reactions are likely to be deposited in the cloud, which becomes enriched in heavier mass nuclei. If these heavier nuclei participate in high temperature nucleosynthesis, significant metal production might be possible. Finally, the wide range of densities which can exist in
the central quasar region could also have a significant effect on any metal production, since thermonuclear reaction rates are dependent not only on the temperature, but also on the density.

In order to determine if extra-solar nucleosynthesis is a viable mechanism for generating metals in quasars, we have implemented a model which combines high temperature nucleosynthesis with the addition of material from the incident jet. Based on the time constraints faced by the stellar models for the highest redshift objects and the presence of alternative nucleosynthesis mechanisms in quasars, the exploration of a model such as ours is well motivated.
CHAPTER 3

The Jet–Clump Interaction Model

In this chapter, we present a non-stellar model for metal production which may operate in the central region of quasars. Our model describes the processes which are expected to occur as a high energy particle jet impinges on a region of hot, relatively dense gas. Two basic processes are at work: ordinary thermal nucleosynthesis in the hot gas, and enhancements to this nucleosynthesis which occur as the non-thermal jet enters the gas. The technique used in modeling the synthesis of elements through thermonuclear processes is now textbook astrophysics, and we summarize the standard formalism and our implementation of it in section 3.2. A different approach is needed to incorporate into the model reactions caused by the collision of the incident jet particles with clump nuclei. The energy distribution of the jet particles is assumed to be a Gaussian with a relatively high mean energy. Nuclei in the gas are essentially at rest with respect to the jet. In Section 3.3, we describe the equations and algorithms necessary for coupling non-thermal jet–clump reactions to the standard thermonuclear processes.

Since our model can involve temperatures and densities above those generally inferred for clouds in the BLR (and thus also the NLR, which is cooler and less
dense), we refrain from using the term "cloud" in reference to the material in which our process could occur. Instead we refer to the region of interest either as a "gas clump", or just a clump. Such regions may exist in the accretion disk (Bednarek & Protheroe 1996a), or in the intersection of the jet with the surface of a star (Bednarek & Protheroe 1996b).

Also, note that in the present work, we focus only on the nuclear processes which could be responsible for generating large metal enrichments in quasars. Determining an emission line spectrum for gas containing the abundances produced by our model would require a full ionization calculation. Previous ionization studies already suggest that metal abundances in the gas surrounding quasar cores may exceed solar levels. We are simply trying to determine if jet-clump interactions in the quasar environment can provide a plausible mechanism for explaining enhanced metal concentrations.

3.1 Model Overview

Our model is composed of two complementary processes: thermal nucleosynthesis and jet-clump interactions. First we motivate the occurrence of each process based on specific characteristics of the quasar environment.

3.1.1 Thermal Nucleosynthesis in the Clump

Gas densities in the central region of quasars may be as high as $10^{18}$ particles/cm$^3$ (Baldwin et al. 1996; Kuncic, Blackman, & Rees 1996; Baldwin et al. 1995; Ferland &:
Rees 1988). Some of this gas can be heated to extremely high temperatures (Kusunose & Mineshige 1994; Kerrick et al. 1995; Kurpiewski, Kuraszkiewicz, & Czerny 1996). especially in the accretion disk (Narayan, Yi, & Mahadevan; Bednarek & Protheroe 1996a; Narayan 1995). Collisions between gas nuclei with thermal velocities can initiate a sequence of nuclear reactions in a process known as thermonuclear nucleosynthesis. Metal production occurs as lighter nuclei react to form various products, some of which may be heavier than the reactants.

Three factors control the effectiveness of thermal nucleosynthesis in generating significant metal abundances in quasars. The temperature is of critical importance, since the reaction rates increase rapidly with temperature. At lower temperatures, many reactions proceed so slowly that they are effectively turned off. At very high temperatures, however, the destruction of nuclei by energetic photons can inhibit production of higher mass elements. Thus a temperature between these extremes is required if net nucleosynthesis is to occur.

Reaction rates also depend (usually linearly) on the density. Higher densities will thus be more effective at rapidly producing metals. Growth in the clump density due to addition of material from the jet can therefore greatly assist the nucleosynthesis.

Finally, thermal nucleosynthesis in the quasar clumps is limited by gaps in the sequence of stable nuclides at mass 5 and 8. Reaching nuclei beyond either of these gaps requires a reaction between sufficiently heavy particles in the entrance channel so that at least one particle in the exit channel is above the mass gap. If the reactants are heavy, then the Coulomb barrier for the reaction will be higher. Reaction rates
decrease dramatically for higher Coulomb barriers, and so metal production across the mass gaps is very limited.

3.1.2 Jet Characteristics

The presence of the jet boosts the nucleosynthesis in several ways. First, the jet can deposit material in the clump, thereby raising the density. Since the confinement mechanism\(^1\) which keeps the gas in clumps is not well understood, the upper limit on the density in this environment is not known. At the present, we treat the final density as a free parameter which can take on values up to \(10^{23}\) particles/cm\(^3\), which is on the order of the density of common terrestrial solids and liquids. The jet also helps alleviate another obstacle to metal production – the lack of stable nuclei at \(A=5\) and \(A=8\). When the energetic particles of the jet enter the cloud, they will be slowed by collisions with the electrons in the gas. However, a fraction of the non-thermal jet particles will also collide with the gas nuclei. These nuclear collisions, which we refer to as jet-clump reactions, can create products with masses above the mass 5 gap. Subsequent collisions between the heavier, non-thermal products of previous jet-clump reactions and gas nuclei can also create nuclei above the mass 8 gap. Furthermore, jet-clump reaction products which do not lie above the mass gaps can still stimulate the nucleosynthesis. The presence of particles such as \(^2\)H and \(^3\)He, which are only expected to be generated in significant quantities by the jet-clump

\(^1\)Magnetic confinement is often cited (Rees 1987) as one possibility for clouds in the BLR. This effect would certainly be important for gas which is fully ionized.
reactions, can open up new reaction pathways to higher mass elements. The high energy jet is therefore essential in boosting the thermal nucleosynthesis in the hot gas clump. Complete details of the jet-clump reactions are given in section 3.3.2.

The mass outflow in the jet is a fraction of the accretion rate, $\dot{M}$, onto the central black hole. Extreme values for $\dot{M}$ in quasars range from $10^{-2}$ to $10^2 \, M_\odot/yr$ (Falcke 1995), with 1 to 10 $M_\odot/yr$ being more typical (Norman & Scoville 1988). Here $M_\odot$ indicates 1 solar mass, or $1.989 \times 10^{33}$g. Since the jet is indeed thought to be closely related to the accretion process (Contopoulos & Kazanas 1995; Blandford 1990), it is no surprise that the jet particles have high energies. Material in the accretion disk descends fairly deeply into the potential of the black hole, where a particle can acquire an energy as high as $0.1 \, mc^2$, i.e., 10% of the rest mass. This corresponds to a kinetic energy of about 100 $\, A\, MeV$, and a Lorentz factor $\gamma$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}} \quad (\text{where } \beta = v/c) \quad (3.1)$$

of about 1.1, and $\beta$ of 0.4

Some quasars exhibit very large scale relativistic outflows, with bulk Lorentz factors as high as 50 (Urry & Padovani 1995). Since such flows are often associated with the Mpc scale\(^2\) of the radio lobes, they represent a much more powerful version of the small centralized phenomena which we consider for our model. We mention them to simply point out that particle acceleration mechanisms in quasars can achieve relativistic energies. Jet energies in our simulations range from 100 $\, A\, MeV$ ($\gamma = 1.1$) up

\(^2\)1 Mpc = 3.26 $\times$ $10^6$ light years. Our galaxy is $10^6$ light years across, and the inner scale of quasars is measured in light days.
to 1000 $A$ MeV ($\gamma = 5$). Since $A$ is the atomic number, quoting an energy as 100 $A$ MeV is the same as saying 100 MeV/amu.

For the distribution of particle energies in the jet, we simply assume it to be a Gaussian with a standard deviation around 10% of the mean energy. A more complex distribution is not warranted since our model is not very sensitive to the exact jet particle energy distribution. First of all, the amounts of interesting nuclei introduced into the clump by jet-clump reactions (see section 3.3.2) depend mainly on the average energy of the incoming particles. Furthermore, since we model the clump as a single, homogenous region (we assume it is mixed on relatively short time scales), we do not keep track of differences in the penetration depth for jet particles of different energy. We are only concerned with whether or not the jet is stopped anywhere in the clump, which also depends primarily on the average energy.

If, however, the cloud is too thin to stop all of the jet particles, then the energy distribution becomes important because it determines what fraction of the jet is deposited in the clump. If only a small fraction of the jet stays in the clump, the density will build up more slowly. Lower density means slower reaction rates and less metal production. For this reason (and for other reasons mentioned in section 3.3.1), the thin clouds do not offer very promising possibilities for nucleosynthesis of metals in the jet-clump scenario. Therefore the exact energy distribution of the jet particles is not crucial, and we assume it to be a Gaussian for simplicity.

Both the jet and the cloud are assumed to be composed of primordial material. Although we do include some of the less abundant primordial constituents, namely
D, \(^3\)He, and \(^7\)Li, they have only limited importance due to their low concentrations. Also, D and \(^7\)Li are relatively fragile and thus may not survive in the pre-jet or pre-clump material as temperatures climb to \(T_\odot \sim 1\). In test cases with the initial abundances of D, \(^3\)He, and \(^7\)Li set to zero, we detect no significant alterations in the metal production. Primordial number abundances are shown in Table 3.1 for all elements \(A < 7\) produced by the big bang.

For primordially produced elements heavier than \(^7\)Li, we assume a zero initial abundance because it simplifies our calculations. Also, the processes in the jet–clump model do not depend on the initial metal concentration, and we are trying to see if the primordial values can be greatly exceeded by the jet–clump interactions. For reference, estimates from Kajino, Matthews, & Fuller (1990) for the the primordial abundances of \(^{12}\)C, \(^{14}\)N, and \(^{16}\)O are about \(10^{-15}\), \(10^{-16}\), \(10^{-19}\) respectively. These are number abundance ratios relative to \(^1\)H.

3.2 Thermal Nucleosynthesis

Sections 3.2 and 3.3 describe the calculations in our model. In this section, we explain the concept of a reaction rate and how to combine many reaction rates into differential equations quantifying the time evolution of nuclidic abundances. The algorithm for solving the coupled set of equations is also given.
<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>0.93</td>
</tr>
<tr>
<td>$^2\text{H}$</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^3\text{He}$</td>
<td>$1.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>$^4\text{He}$</td>
<td>0.07</td>
</tr>
<tr>
<td>$^7\text{Li}$</td>
<td>$1.0 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Table 3.1: Primordial number abundances employed in our model. The essential components of the jet are $^1\text{H}$ and $^4\text{He}$. Also, the effect of small initial concentrations in the clump of particles other than $^1\text{H}$ and $^4\text{He}$ is negligible. Higher mass elements such as Be, B, C, and O do have nonzero primordial abundances in the standard hot big bang scenario, but they are extremely low and production in our model in not very sensitive to the the initial metal concentration.

### 3.2.1 Nuclear Reaction Rates

The concept of a nuclear reaction rate can be explained in the following way. Picture a block of particle species $y$, with $N_y$ particles/cm$^3$. A beam of incident particles of type $x$ with velocity $v$ and $N_x$ total particles impinges on the left surface of the block. Figure 3.1 illustrates this situation. If the cross section for interactions between particles $x$ and $y$ is given by $\sigma(v)$, then each $x$ particle sees a total reaction area of $\sigma(v)N_y$. Each $y$ in turn sees an incident flux of $vN_x$ particles per second, and so the total reaction rate is $N_xN_yv\sigma(v)$. If the incident particles $x$ have a velocity distribution $\phi(v)$, which is normalized to 1.

$$\int \phi(v) \, dv = 1.$$  \hspace{1cm} (3.2)
Figure 3.1: \( N_x \) particles are incident on a block of \( N_y \) targets per \( \text{cm}^3 \). The rate of nuclear reactions between \( x \) and \( y \) is given as \( N_x N_y \nu \sigma(v) \) if all \( x \) particles have the same velocity \( v \).

then the reaction rate will be

\[
\langle \sigma v \rangle = N_x N_y \int \sigma(v) v \phi(v) \, dv. \tag{3.3}
\]

Since only the relative velocity between the projectile and target determines the reaction rate, a similar approach will work if both the \( x \) and \( y \) particles have a distribution of velocities. In a thermalized gas, both the \( x \) and \( y \) velocity distributions have a Maxwell-Boltzmann shape, as does the distribution of relative velocities between the two particles. In this case, the final expression for the reaction rate per particle pair is

\[
\langle \sigma v \rangle = \left( \frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E e^{-\frac{E}{kT}} \, dE. \tag{3.4}
\]
where $E$ has been substituted for $v$, $\mu$ is the reduced mass of the two particles $\mu = m_x m_y/(m_x + m_y)$, $k$ is Boltzmann's constant, and $T$ is the temperature in Kelvin. A complete derivation of this key equation is provided in Rolfs & Rodney (1988). Given the rate per particle pair, the total rate for reactions between two particles $x$ and $y$ is then

$$N_x N_y \langle \sigma v \rangle.$$ (3.5)

All of the nuclear physics within the reaction rate per particle pair is contained in the cross section $\sigma(E)$, which appears inside the integral of equation 3.4. Cross sections can be measured or calculated, and often require careful extrapolation to the very low energies relevant for astrophysical processes. Given $\sigma(E)$, values of $\langle \sigma v \rangle$ are calculated for various temperatures, and a function describing $\langle \sigma v \rangle$ over the relevant temperature range is fit to these values. Tabulations of functions yielding $N_A \langle \sigma v \rangle$ as a function of $T_9$ for many different reactions can be found in the literature (Caughlan & Fowler 1988; Wagoner 1969; Wagoner, Fowler, & Hoyle 1967; Harris et al. 1983; Fowler, Caughlan, & Zimmerman 1975; Fowler, Caughlan, & Zimmerman 1967). $T_9$ is the temperature in billion Kelvin, and $N_A$ is Avagadro’s number, which is included for reasons which will become apparent below. Figure 3.2 shows several reaction rates which are important in the jet–clump model.

We pause here to point out that $\langle \sigma v \rangle$ for charged particle reactions is often extremely dependent on the temperature. Thus as the temperature increases, some reactions which were negligible at lower temperatures may suddenly turn on and produce significant changes in the reaction pathways. We mention this here because we
Figure 3.2: Reaction rates as a function of temperature for selected reactions as quoted in the literature. $T_g$ is in billion Kelvin. Notice the sensitivity of each rate on the temperature - the ordinate ranges over 34 orders of magnitude. The dashed curve gives $\lambda_{7\gamma}$, the rate of photodestruction of $^7\text{Be}$ as a function of temperature (i.e., the inverse rate for reaction b).
will show (in Chapter 4) that our results are fairly sensitive to the temperature, and
the underlying source of this sensitivity is the critical dependence of the reaction rates
themselves on the temperature.

\( \langle \sigma v \rangle \) as described thus far gives the reaction rate for the forward reaction, which
usually refers to the direction which has positive \( Q \)-value\(^3\).

\[
\text{forward reaction: } 1 + 2 \rightarrow 3 + 4 \quad \text{with } Q > 0 \quad (3.6)
\]

\[
\text{reverse reaction: } 3 + 4 \rightarrow 1 + 2 \quad \text{with } Q < 0 \quad (3.7)
\]

The reverse process for many nuclear reactions becomes increasingly relevant in
thermal nucleosynthesis at higher temperatures where the higher particle energies can
balance the effect of the negative \( Q \)-value. In our model it is absolutely essential to
include reverse reactions.

A reverse reaction is related to the forward reaction by the principle of detailed
balance, which states that the nuclear physics between two specific nuclear states in
the forward transition is the same as that in the reverse transition\(^4\). The forward
and reverse rates are related to each other, then, by statistical factors indicating the
number of spin states available in the entrance and exit channels. For the above two
body reaction with a positive \( Q \) value, the reverse reaction rate is

\[
\langle \sigma v \rangle_{34} = \langle \sigma v \rangle_{12} \frac{m_1 m_2 E_{12}(2J_1 + 1)(2J_2 + 1)}{m_3 m_4 E_{34}(2J_3 + 1)(2J_4 + 1)}. \quad (3.8)
\]

\(^3\)The \( Q \)-value is the energy equivalent to the difference in mass between the reactants and products.
A positive \( Q \)-value means that energy is given off as the reactants are changed into products, while
a reaction with a negative \( Q \)-value requires energy in order to proceed.

\(^4\)Note, though, that this is technically correct only for reactions between specific states. Generally
forward and reverse reactions will not involve all of the same states.

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Tabulations of $N_A(\sigma v)$ also list functions for the reverse rate.

### 3.2.2 Reaction Networks

The goal of a nucleosynthesis calculation is to generate abundance versus time values for each nuclide present in the gas. In order to simulate thermonuclear nucleosynthesis in a hot gas, information characterizing the following is required:

1. initial concentrations of all nuclei
2. the temperature, which in general can change as a function of time
3. the density as a function of time
4. all relevant transitions between the various types of nuclei which are initially present or subsequently created in the gas: this includes nuclear reaction rates, and beta decay rates (and also jet-clump reactions – see section 3.3.2)

The initial abundances are assumed to be primordial. The gas temperature is kept constant in our model in order to simplify the calculations. Constant temperatures from $T_g = 0.1$ to $T_g = 5.0$ are explored. The initial density of the gas is also varied as a parameter. The way in which the density changes with time is a more complicated issue which will be discussed further in section 3.3.1, which deals with the issues related to the interaction of the jet and the gas clump. Briefly, the density may continue to increase as material from the jet fills the clump, or, if there is sufficient outflow from the clump, the density may climb to a maximum value and then level off as a balance is achieved between inflow and outflow.
The reactions we use are those relevant for a hot gas containing light particles (i.e., protons, neutrons, and alphas). The reactions on lower mass nuclei \(A=1\) to \(12\) are similar to those which occurred in the big bang and are taken directly from the well known and well tested big bang code of Kawano (1989). The reactions on nuclei from \(A=12\) to \(24\) are those of the hot CNO cycle as described in Wiescher & Kettner (1982). All reactions used and the ultimate source of each in the literature are listed in Tables 3.2 through 3.4.

Several of the reaction rates quoted in Caughlan & Fowler (1988) contain unknown factors which can range from 0 to 1. These factors are primarily found in reactions involving unstable nuclei, whose cross sections can be difficult to measure. However, the thermonuclear pathways in our model do not depend critically on any of these reaction rates. As suggested in Caughlan & Fowler (1988), we set all such factors to 0.1.

Given a list of relevant nuclear reactions, the next step is to set up, for each nuclide, a rate equation which determines the time rate of change of that nuclide’s abundance. The terms in a nuclide’s rate equation are reaction rates or beta decay rates for every transformation which either uses the nuclide in the input channel or produces the nuclide in the exit channel. The inverse of many nuclear reactions must also be considered, especially at high temperatures where the forward and reverse rates are often comparable.
Nuclear Network Reactions I – Weak Decays

<table>
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<th>Name</th>
</tr>
</thead>
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<td>1</td>
<td>( n \rightarrow p )</td>
<td>12</td>
<td>( ^7\text{Be} \rightarrow ^7\text{Li} ) †</td>
</tr>
<tr>
<td>2</td>
<td>( ^3\text{H} \rightarrow ^3\text{He} )</td>
<td>13</td>
<td>( ^{17}\text{F} \rightarrow ^{17}\text{O} )</td>
</tr>
<tr>
<td>3</td>
<td>( ^8\text{Li} \rightarrow 2 \ 4\text{He} )</td>
<td>14</td>
<td>( ^{18}\text{F} \rightarrow ^{18}\text{O} )</td>
</tr>
<tr>
<td>4</td>
<td>( ^{6}\text{B} \rightarrow 2 \ 4\text{He} )</td>
<td>15</td>
<td>( ^{18}\text{Ne} \rightarrow ^{18}\text{F} )</td>
</tr>
<tr>
<td>5</td>
<td>( ^{12}\text{N} \rightarrow ^{12}\text{C} )</td>
<td>16</td>
<td>( ^{19}\text{Ne} \rightarrow ^{19}\text{F} )</td>
</tr>
<tr>
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<td>( ^{14}\text{O} \rightarrow ^{14}\text{N} )</td>
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<td>( ^{20}\text{Na} \rightarrow ^{20}\text{Ne} )</td>
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<tr>
<td>7</td>
<td>( ^{11}\text{C} \rightarrow ^{11}\text{B} )</td>
<td>18</td>
<td>( ^{21}\text{Na} \rightarrow ^{21}\text{Ne} )</td>
</tr>
<tr>
<td>8</td>
<td>( ^{12}\text{B} \rightarrow ^{12}\text{C} )</td>
<td>19</td>
<td>( ^{22}\text{Na} \rightarrow ^{22}\text{Ne} )</td>
</tr>
<tr>
<td>9</td>
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<td>( ^{22}\text{Mg} \rightarrow ^{22}\text{Na} )</td>
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<td>( ^{23}\text{Mg} \rightarrow ^{23}\text{Na} )</td>
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<td>11</td>
<td>( ^{15}\text{O} \rightarrow ^{15}\text{N} )</td>
<td>22</td>
<td>( ^{24}\text{Al} \rightarrow ^{24}\text{Mg} )</td>
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</tbody>
</table>

Table 3.2: Weak decays included in the reaction network. † Note that the \(^7\text{Be} \) decay is by electron capture, which progresses much more slowly at high temperatures and low densities. See the text for the implications of inhibited \(^7\text{Be} \) decay in our model. The formula for this decay is given in Rolfs & Rodney (1988). All other rates come from Tuli (1995).
**Nuclear Network Reactions II - Low Mass Thermonuclear Reactions**

<table>
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<td>43</td>
<td>(^7)Li (d,(\alpha))(^2)H</td>
<td>b</td>
<td>70</td>
<td>(^{12})H (2(\alpha),(\gamma))(^12)C</td>
<td>b</td>
<td>96</td>
<td>(^{10})B ((\alpha),n)(^13)N</td>
<td>b</td>
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<tr>
<td>44</td>
<td>(^7)Be (d,(\alpha))(^4)H</td>
<td>b</td>
<td>71</td>
<td>(^8)Li (p,(\alpha))(^n)</td>
<td>d</td>
<td>97</td>
<td>(^{11})B ((\alpha),n)(^14)N</td>
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<td>c</td>
<td>72</td>
<td>(^8)B (n,(\alpha))(^1)H</td>
<td>d</td>
<td>98</td>
<td>(^{12})B ((\alpha),n)(^15)N</td>
<td>a</td>
</tr>
<tr>
<td>46</td>
<td>(^{10})B (n,(\gamma))(^11)B</td>
<td>a</td>
<td>73</td>
<td>(^9)Be (p,(\alpha))(^2)H</td>
<td>b</td>
<td>99</td>
<td>(^{13})C ((\alpha),n)(^16)O</td>
<td>b</td>
</tr>
<tr>
<td>47</td>
<td>(^{11})B (n,(\gamma))(^12)B</td>
<td>c</td>
<td>74</td>
<td>(^{11})B (p,(\alpha))(^4)He</td>
<td>b</td>
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</tr>
</tbody>
</table>

Table 3.3: Nuclear reactions in the lower mass portion of the network. References are as follows: a is Wagoner (1969), b is Caughlan & Fowler (1988), c is Malaney & Fowler (1989), d is Kawano (1989).
### Nuclear Network Reactions III – High Mass Thermonuclear Reactions

<table>
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<tr>
<th>#</th>
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<th>#</th>
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<td>$^{16}\text{O}(p,\gamma)^{17}\text{F}$</td>
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<td>119</td>
<td>$^{17}\text{F}(\alpha,p)^{20}\text{Ne}$</td>
<td>b</td>
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<td>b</td>
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<td>$^{18}\text{F}(\alpha,p)^{21}\text{Ne}$</td>
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<td>121</td>
<td>$^{19}\text{F}(\alpha,p)^{22}\text{Ne}$</td>
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</tr>
<tr>
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<td>$^{17}\text{F}(p,\gamma)^{18}\text{Ne}$</td>
<td>f</td>
<td>122</td>
<td>$^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$</td>
<td>f</td>
</tr>
<tr>
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<td>$^{18}\text{F}(p,\gamma)^{19}\text{Ne}$</td>
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<td>123</td>
<td>$^{19}\text{Ne}(\alpha,p)^{22}\text{Na}$</td>
<td>a</td>
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<tr>
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<td>b</td>
<td>128</td>
<td>$^{14}\text{C}(\alpha,\gamma)^{18}\text{O}$</td>
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<td>b</td>
</tr>
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<tr>
<td>116</td>
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<td>135</td>
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<tr>
<td>117</td>
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<td>a</td>
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<td>$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$</td>
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</tr>
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<td>118</td>
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<td>137</td>
<td>$^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}$</td>
<td>b</td>
</tr>
</tbody>
</table>

Table 3.4: Nuclear reactions in the higher mass portion of the network. References are as follows: a is Wagoner (1969). b is Caughlan & Fowler (1988). f is Wagoner, Fowler, & Hoyle (1967).
As an example of how to construct nuclidic rate equations, consider the following list of prototypical reactions:

\[ 1 + 2 \rightarrow 3 + 4 \quad (\text{strong reaction}) \]  
\[ 1 \rightarrow 2 \quad (\beta \text{ decay}) \]  
\[ 1 + 3 \rightarrow 5 + \gamma \quad (\text{electromagnetic capture}) \]

These three processes involving 5 nuclides illustrate the main types of reactions which occur in reaction networks. Let \( n_i \) represent the number abundance in particles per cm\(^3\) of species \( i \), and \( \langle \sigma v \rangle_{ij} \) the reaction rate per particle pair with particle \( i \) and \( j \) in the entrance channel. The rate equations for nuclides 1 through 5 can be written as follows:

\[
\frac{dn_1}{dt} = -n_1n_2 \langle \sigma v \rangle_{12} + n_3n_4 \langle \sigma v \rangle_{34} - n_1\lambda_1 - n_1n_3 \langle \sigma v \rangle_{13} + n_5\lambda_{5\gamma} \tag{3.12}
\]

\[
\frac{dn_2}{dt} = -n_1n_2 \langle \sigma v \rangle_{12} + n_3n_4 \langle \sigma v \rangle_{34} + n_1\lambda_1 \tag{3.13}
\]

\[
\frac{dn_3}{dt} = +n_1n_2 \langle \sigma v \rangle_{12} - n_3n_4 \langle \sigma v \rangle_{34} - n_1n_3 \langle \sigma v \rangle_{13} + n_5\lambda_{5\gamma} \tag{3.14}
\]

\[
\frac{dn_4}{dt} = +n_1n_2 \langle \sigma v \rangle_{12} - n_3n_4 \langle \sigma v \rangle_{34} \tag{3.15}
\]

\[
\frac{dn_5}{dt} = +n_1n_3 \langle \sigma v \rangle_{13} - n_5\lambda_{5\gamma} \tag{3.16}
\]

Note that the symbol \( \lambda \) serves double duty as \( \lambda_1 \), the decay constant for the beta decay in reaction 3.10, and as \( \lambda_{5\gamma} \), the lifetime against photodestruction for particle 5 (i.e., the inverse of reaction 3.11.)

The first reaction 3.9 is a simple two body reaction. The net rate for this reaction is

\[
R_{1234} = n_1n_2 \langle \sigma v \rangle_{12} - n_3n_4 \langle \sigma v \rangle_{34}. \tag{3.17}
\]
Note that this combination of forward and reverse rates appears in the rate equation of each of the four nuclides affected by this reaction. Since 3.9 destroys particles 1 and 2, the rate equation for these particles contains $-R_{1234}$.

The beta decay in 3.10 affects only nuclides 1 and 2, and does not have an inverse process since beta decay is only reversible by neutrino capture, and the neutrinos do not play a significant role in quasar gas.

The electromagnetic capture in 3.11 affects the production of three nuclides, and has a net rate of

$$R_{1357} = n_1 n_3 (\sigma v)_3 - n_5 \lambda_{57}.$$  \hspace{1cm} (3.18)

which appears in equations 3.12 and 3.14 with a minus sign and equation 3.16 with a plus sign.

The equations connecting a set of nuclides through various reaction rates are usually referred to as a nuclear reaction network, or simply a reaction network. Our reaction network contains 45 nuclei, and we do not attempt to show the equations for each of these.

One crucial aspect of the thermonuclear processes in our model is the survival of $^7\text{Be}$. Since it lies between the stability gaps at $A = 5$ and $A = 8$, $^7\text{Be}$ serves as an essential stepping stone from lower to higher masses. Atomic $^7\text{Be}$ decays by capturing a K-shell electron with a lifetime of 53.3 days. But if the nucleus is fully stripped of its orbiting electrons, the captured electron must come from the surrounding continuum. In this case, the lifetime depends on the temperature $T_9$, the mass density $\rho$, and the metallicity of the gas (expressed as a function of the hydrogen mass fraction $X_H$).
which together determine the availability of the surrounding electrons. The formula for the lifetime $T_{7\text{Be}}$ of fully ionized $^7\text{Be}$ in a plasma is given by Rolfs & Rodney (1988) as

$$T_{7\text{Be}} = 1.49 \times 10^{10} \frac{T_{9}^{1/2}}{\rho (1 + X_H)} \text{ s.} \quad (3.19)$$

$X_H$ ranges from 0 to 1, and therefore will not greatly affect the lifetime. At $T_9 = 0.2$, $\rho = 10^{-6} \text{ g/cm}^3$, and $X_H = 1.0$, $T_{7\text{Be}} = 3.33 \times 10^{13} \text{ s} = 1.06 \times 10^8 \text{ yr}$, which is more than long enough for the $^7\text{Be}$ to fully participate in the thermal nucleosynthesis of quasar clumps.

### 3.2.3 Solving the Equations

As can be seen in equations 3.12 to 3.16, the time evolution of nuclidian abundances in a reaction network is governed by a set of coupled, non-linear, ordinary differential equations\(^5\). For any reasonable number of nuclei and reactions, obtaining an analytic solution is utterly impractical. We present here the standard algorithm for solving such a network numerically. This description is based on a study of the method as presented in Bowers & Wilson (1991), Woosley, Arnett, & Clayton (1973), and Arnett & Truran (1969).

The following example illustrates the process of creating the equations for the time rate of change of each nuclide’s abundance. Assume that in all the specified

\[^5\text{The equations are coupled because the rate of change of one nuclear abundance depends in general on the abundance of many other nuclei. The equations are non-linear because terms for two body or higher reactions contain abundances to the second power. (This is especially clear if identical particles are involved – see equation 3.21.) Finally, these are ordinary differential equations because no partial derivatives are present.}\]
reactions, there are $N$ different nuclear species. If nuclide $i$ participates in only two body reactions, its rate equation will look like

$$\frac{d}{dt} n_i = - \sum_j n_i n_j \langle \sigma v \rangle_{ij} + \sum_{kl} n_k n_l \langle \sigma v \rangle_{kl}. \quad (3.20)$$

where $n_i$ is the number abundance of $i$ in particles/cm$^3$, and so on for $j$, $k$, and $l$. $\langle \sigma v \rangle_{ij}$ is the reaction rate per particle pair for destruction of $i$ and $j$, and $\langle \sigma v \rangle_{kl}$ is the reaction rate per pair of particles $k$ and $l$, which combine to produce $i$ (but not necessarily $j$). The sum over $j$ includes all the reactions which destroy $i$ and the sum over $k$ and $l$ includes all the reactions which produce $i$. If the entrance channel to a reaction involves two identical particles, then the substitution

$$n_i n_j \Rightarrow \frac{n_i^2}{2} \quad (3.21)$$

is necessary to avoid incorrectly counting the number of distinguishable particle pairs.

For terms in the rate equation representing processes other than two body interactions such as beta decay, electromagnetic capture, or three body reactions, a similar approach to that developed below can be used. Detailed derivations for these terms are not shown here.

Since the number abundances $n_i$ can be large, and hence numerically cumbersome, it is preferable to use the mole fraction, $Y_i$,

$$Y_i = \frac{n_i}{\rho N_A}, \quad (3.22)$$

where $\rho$ is the mass density in g/cm$^3$, and $N_A$ is Avagadro's number. The above relation also implies that the $Y_i$'s are related to the mass fractions $X_i$ by $Y_i = X_i/A_i$, where $A_i$ is the atomic number of nuclide $i$. 

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Substituting for the number abundances in equation 3.20, one obtains

\[
\frac{dY_i}{dt} = - \sum_j Y_i Y_j r_{ij} + \sum_{kl} Y_k Y_i r_{kl},
\]  

(3.23)

with \( r_{ij} = \rho N_A \langle \sigma v \rangle_{ij} \). Here then is the reason why the tabulations (see the captions of Tables 3.2 through 3.4 for references of the tabulations) quote reaction rates per particle pair as \( N_A \langle \sigma v \rangle \).

The desired quantities are the abundances \( Y_i^n \), computed at various time steps, \( t^n \), where the superscript \( n \) refers to values at the current time step, and a superscript of \( n + 1 \) refers to the next time step. The simplistic approach would be to evaluate each time derivative \( dY_i/dt \) using equation 3.23 and the abundance values \( Y_i^n \) at the current time step. Mole fractions \( Y_i^{n+1} \) at the next time would simply be

\[
Y_i^{n+1} = Y_i^n + \Delta t \frac{dY_i}{dt}.
\]  

(3.24)

However, abundances obtained in this way are numerically unstable so that small errors can be amplified over time, making the final results meaningless. Such an approach is called an explicit approach.

Instead, an implicit method is required. For this method, the values at the next time step are substituted into the right hand side of equation 3.23. The time derivative is then re-written as \( \Delta_i/\Delta t \) such that \( \Delta_i = Y_i^{n+1} - Y_i^n \) and \( \Delta t = t^{n+1} - t^n \). Equation 3.23 then becomes

\[
\frac{\Delta_i}{\Delta t} = - \sum_j Y_i^{n+1} Y_j^{n+1} r_{ij} + \sum_{kl} Y_k^{n+1} Y_i^{n+1} r_{kl}.
\]  

(3.25)
Abundance values $Y_i^{n+1}$ at the next time step are sprinkled throughout this equation. The problem now is rearrange all $N$ of these equations to simultaneously solve for each $Y_i^{n+1}$.

If the time step is small enough that the changes $\Delta_i$ are also small, then each $Y_i^{n+1}$ on the right hand side can be replaced by $Y_i^n + \Delta_i$:

$$\frac{\Delta_i}{\Delta t} = - \sum_j (Y_i^n + \Delta_j)(Y_j^n + \Delta_j)r_{ij} + \sum_{kl}(Y_k^n + \Delta_k)(Y_l^n + \Delta_l)r_{kl} \quad (3.26)$$

The crucial step in this algorithm is dropping all terms of order $\Delta_i^2$ or higher.

because this effectively linearizes the equations.

$$\frac{\Delta_i}{\Delta t} = - \sum_j (Y_i^nY_j^n + Y_i^n\Delta_j + Y_j^n\Delta_i)r_{ij}$$

$$\frac{\Delta_i}{\Delta t} = - \sum_j \{Y_i^nY_j^n + Y_i^n(Y_j^{n+1} - Y_j^n) + Y_j^n(Y_i^{n+1} - Y_i^n)\}r_{ij}$$

$$\frac{Y_i^{n+1} - Y_i^n}{\Delta t} = - \sum_j \{-Y_i^nY_j^n + Y_i^{n+1}Y_j^n + Y_j^{n+1}Y_i^n\}r_{ij}$$

$$+ \sum_{kl}(-Y_k^nY_l^n + Y_k^{n+1}Y_l^n + Y_l^{n+1}Y_k^n)r_{kl} \quad (3.29)$$

$$\quad \quad (3.30)$$

When all terms involving the unknowns ($Y_i^{n+1}, Y_j^{n+1}, Y_k^{n+1}$, and $Y_l^{n+1}$) are moved to the left hand side, we obtain

$$Y_i^{n+1} \left( \frac{1}{\Delta t} + \sum_j Y_j^n r_{ij} \right) + \sum_j Y_j^{n+1}(Y_i^n r_{ij}) - \sum_{kl} Y_k^{n+1}(Y_i^n r_{kl}) - \sum_{kl} Y_l^{n+1}(Y_i^n r_{kl})$$

$$= \frac{Y_i^n}{\Delta t} + \sum_j (Y_i^n Y_j^n r_{ij}) - \sum_{kl}(Y_k^n Y_i^n r_{kl}). \quad (3.31)$$

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Thus the $N$ coupled, non-linear differential equations have been transformed into a set of coupled, linear, algebraic equations with $N$ unknowns (i.e., the $Y_i^{n+1}$ for each nuclide). Gaussian elimination or any numerically equivalent algorithm can be used to solve this set of equations. In our code, we utilize the standard IMSL library routine DLSARG.

### 3.2.4 Time Step Adjustment and Abundance Accuracy

Terms of order $\delta_i^2 = (\Delta_i/Y_i)^2$ are ignored in linearizing the rate equations. To insure small changes in each $Y_i$, the rate of change of $Y_i$ must be much smaller than $Y_i$ itself.

$$\frac{dY_i}{dt}\Delta t \ll Y_i \quad (3.32)$$

The derivative is evaluated at the current time step, and the most recent value of $Y_i$ is used on the right hand side. Thus the constraint on the next time step $\Delta t_{\text{next}}$ is that

$$\frac{\Delta_i}{\Delta t_{\text{now}}} \ll \frac{Y_i^{n+1}}{\Delta t_{\text{next}}} \quad (3.33)$$

for all relevant species. If $\epsilon$ is a parameter much less than 1, then the next time step can be calculated as

$$\Delta t_{\text{next}} = \epsilon \Delta t_{\text{now}} \, \text{MIN} \left[ \frac{Y_i^{n+1}}{\Delta_i} \right] \quad (3.34)$$

Finding the minimum value of $Y_i^{n+1}/\Delta_i$ insures that the next time step is chosen to be small enough so that even the nuclide whose abundance changes the most rapidly will still satisfy equation 3.32. Possible values of $\epsilon$ range from 0.01 to 0.2, and, following
the example of Bowers & Wilson (1991) and Woosley, Arnett, & Clayton (1973). we typically use 0.1 in our calculations.

In practice, it is possible to speed up the calculation without affecting the accuracy by only allowing nuclides with $Y_i^{n+1} > 10^{-10}$ to participate in the time step evaluation. In order to keep the time step from increasing too rapidly when the nuclides are not varying rapidly, the next time step is restricted to be at most a factor of two greater than the current time step.

Even though the terms neglected in linearizing the abundance evolution equations are of order $\delta_i^2$, the errors for most nuclides are much smaller than this. Many reactions involve protons or alpha particles, whose abundances change more slowly than those of other nuclei. Thus $\delta_j = \Delta_j/Y_j$ for both protons and alphas is also smaller than for the rapidly changing species. Terms for these reactions which are neglected in the calculation look like

$$\delta_i\delta_j = (\Delta_i/Y_i)(\Delta_j/Y_j), \quad (j \text{ is } ^1\text{H or } ^4\text{He}, \text{ } i \text{ is any other nuclide}). \quad (3.35)$$

and, since $\delta_j$ is usually much less than $\delta_i$, the net error is smaller than $\delta_i^2$.

### 3.2.5 Testing

Our code was tested through comparison with published results of other implementations of reaction network codes. For most of these codes, it is now very difficult to obtain the same values for the reaction rates as were originally used. Nevertheless,
Figure 3.3: Abundance evolution at constant temperature and constant density showing good agreement with Wiescher & Kettner (1982). As in their Figure 3, the temperature is $T_g = 0.1$, and the mass density is $\rho = 100 \text{ g/cm}^3$. The y-axis is time, and the x-axis is mass fraction, $X_i$, where $i$ is any of the species shown. Mass fractions are related to the mole fraction by $Y_i = X_i / A_i$, and all $X_i$'s should add up to one: $\sum_i X_i = 1$. 
good agreement is obtained with the results of Wiescher & Kettner (1982), as shown in Figure 3.3 (compare to their Figure 3).

A consistency check can be done to see if the code conserves baryon number, which also is individually conserved in each reaction simulated. In all of our results, baryon number is conserved to better than one part in $10^{13}$.

3.3 Jet—Clump Interactions

Thermonuclear metal generation in the hot gas of a quasar clump is boosted by two processes which occur as a high energy particle jet impinges on the clump. If the gas can slow and stop the jet material, then the clump density may increase. We refer to this process as mass deposition. A higher density will speed up the reaction rates, allowing for faster metal production. Also, nuclei in the jet may strike the clump nuclei, initiating what we call jet-clump reactions. The products of these reactions can serve as key building blocks for assembling higher mass elements. Section 3.3.1 describes the first process, and section 3.3.2 the second.

3.3.1 Mass Deposition in the Clump

The mass deposition process occurs if the clump has sufficient column density to stop at least some of the incident jet particles, which we assume to have a Gaussian energy distribution. Factors affecting the rate of deposition include the following:

1. the volume of the clump
2. the column density of the clump

3. the mass input rate of the jet

4. the initial energy of the jet

5. the energy loss mechanism for jet particles passing through the clump

Parameters 1 and 3 are interrelated because we employ a single zone model in which all the material deposited by the jet is distributed evenly throughout the entire clump. The total mass input rate per cm$^3$, which we refer to as $\dot{M}$, increases not only for more massive jets, but for smaller clump volumes. Assuming that all of the jet stops in the clump, $\dot{M}$ can be the same for different combinations of clump size and jet mass input rate. Therefore, not all values chosen for these parameters will produce unique results. The dependencies between these and other model parameters are discussed further in Chapter 4, in which the metal production results for a variety of parameter combinations are presented.

A jet entering a dense region of gas suggests a cylindrical geometry, and therefore we use a clump of just this shape. This allows the volume and the thickness of the clump to be adjusted independently. No other special considerations are necessary in choosing a clump shape.

The remaining parameters – the column density of the clump, the initial energy of the jet particles, and the energy loss mechanism – are used to determine what fraction of the jet mass is stopped by the gas in the clump. The jet particles enter the clump with a Gaussian energy distribution, which we model as a discrete collection
of monoenergetic jets, each containing an appropriate fraction of the total jet mass. Given the initial energy of a component, the thickness (in particles/cm², i.e., the column density) of the clump, and a method for determining the energy loss through that thickness, the final energy of each component can be found via an energy loss calculation (energy loss is described later in this section). Basically, the portion of the jet stopped in the clump is just the sum of the discrete components whose particles have a final energy of zero. Any fraction of the component which is destroyed in jet-clump reactions is not included in the deposition, but is subtracted out before the jet stops. The procedure for incorporating this subtraction into the deposition process is described later in section 3.3.2.

Another useful concept in discussing the mass deposition is the range of an ion in a stopping medium. The range is proportional to the inverse of the energy loss and is given by

\[ R = \int_{0}^{E_{in}} \frac{dE}{\epsilon} \]  

(3.36)

where \( E_{in} \) is the energy in MeV of the ion as it enters the stopping medium, and the energy loss \( \epsilon \) (defined in detail below) is in MeV/(electrons/cm²). To get a feel for a typical value of the range in our simulation, assume that the energy loss is roughly constant (this is not too far off – see Figure 3.4a) at \( 10^{-23} \) MeV/(electrons/cm²). In this case, a 1000 MeV proton will stop in a clump with a thickness of at least \( 10^{26} \) electrons/cm². For much higher column densities, the jet will be stopped in the front face of the clump. Here our one zone model forces us to assume that this deposited material is subsequently mixed into the rest of the gas.
Energy Loss Mechanism

It is important to understand how jet particles lose energy in the clump because, as just mentioned, the energy loss plays a key role in allowing mass from the jet to build up in the clump. Furthermore, the fraction of jet particles which undergo jet-clump reactions will be shown to depend inversely on the energy loss\(^6\). Thus the energy loss plays a central role in the jet-clump interaction model.

Several candidates exist for the mechanism through which jet nuclei (also referred to as jet ions, or just ions) can lose energy to the electrons in the clump. Ordinary atomic energy loss is not applicable, because the clump gas is fully ionized at temperatures of \(T_9 \approx 1.0\). Therefore, energy loss due to electrons in a plasma must be considered. The way in which an ion loses energy in a plasma depends heavily on the speed of the ion, \(v_{\text{ion}}\), as compared to the average thermal velocity of the electrons, \(\bar{v}_e\). Energy loss formulas for fast ions (\(v_{\text{ion}} \gg \bar{v}_e\)) and slow ions (\(v_{\text{ion}} \ll \bar{v}_e\)) are available in Zweibel & Haber (1983), Ginzburg & Syrovatskii (1964), and Post (1956). Substituting in for the physical constants in formula 7.6 of Ginzburg & Syrovatskii (1964), the fast ion formula is

\[
\epsilon = \frac{1}{n_e} \frac{dE}{dx} = -2.5 \times 10^{-25} \frac{Z_{\text{ion}}^2}{\beta_{\text{ion}}^2} \ln \left( \frac{\beta_{\text{ion}}}{n_e} \right).
\]

\(^6\)Briefly, the yield of a jet clump reaction (i.e., the number of product nuclei created) is proportional to the number of target atoms through which the projectile passes. Thus, the higher the energy loss, the lower the yield since a higher energy loss means that the projectile will go through less target material before stopping.
while their equation 7.9, the slow ion formula, can be expressed as

$$
\epsilon = \frac{1}{n_e} \frac{dE}{dx} = -5.67 \times 10^{-23} \alpha(T_9) \frac{(\gamma_{ion} - 1)}{\beta_{ion}} Z_{ion}^2.
$$

In both equations, the energy loss $\epsilon$ is in MeV/(electrons/cm$^2$). Also, $n_e$ is the electron number density in electrons/cm$^2$, and $T_9$ is the temperature in billion Kelvin. $Z_{ion}$, $\beta_{ion}$, and $\gamma_{ion}$ are, respectively, the charge, velocity (in $v/c$), and Lorentz factor

$$
\gamma_{ion} = \frac{1}{\sqrt{1 - \beta_{ion}^2}}
$$

for the incident ion. The temperature factor $\alpha(T_9)$ in 3.38 is given by

$$
\alpha(T_9) = \frac{(\frac{3}{2}kT_9 + 1)}{T_9 \sqrt{\frac{3}{2}kT_9(\frac{3}{2}kT_9 + 2)}}.
$$

Since the temperature is expressed as $T_9$, Boltzmann's constant $k$ has the value 0.0862 MeV per billion Kelvin.

For comparison purposes, the atomic energy loss $\epsilon$ in MeV/(atoms/cm$^2$) of ions moving through non-ionized material (assuming that the ion speed is much greater than the orbital speed of the electrons) is given by Leo (1987) as

$$
\epsilon = \frac{1}{n_a} \frac{dE}{dx} = -2.55 \times 10^{-25} \frac{Z_{ion}^2}{\beta_{ion}^2} \sum_{j=1}^{N} f_j z_j \ln \left[ \frac{\left(2m_e c^2 \gamma_{ion} \beta_{ion}^2 I_{j}^2 \right) W_{max}}{I_j^2} - 2\beta_{ion}^2 \right].
$$

where $n_a$ is the total atomic density. $f_j$ and $z_j$ are the number fraction and charge of atom $j$ in the $N$ component stopping medium. $m_e$ is the mass of an electron (in MeV/c$^2$), and $\gamma_{ion}$ is again the Lorentz factor. Also, $I_j$ and $W_{max}$ are

$$
I_j = \begin{cases} 
(12z_j + 7) \times 10^{-6} \text{ MeV} & \text{for } z_j < 13 \\
(9.76z_j + 58.8z_j^{-0.19}) \times 10^{-6} \text{ MeV} & \text{for } z_j \geq 13 
\end{cases}
$$
\[ W_{\text{max}} = \frac{2m_e c^2 \beta_{\text{ion}}^2 \gamma_{\text{ion}}^2}{1 + 2(m_e/M_{\text{ion}}) \sqrt{1 + \beta_{\text{ion}}^2 \gamma_{\text{ion}}^2 + (m_e/M_{\text{ion}})^2}}. \] (3.41)

The three types of energy loss can be easily compared by examining Figure 3.4, which shows \( \epsilon \) for \(^1\text{H}\) and \(^4\text{He}\) ions in panels a and b respectively. Since \( \epsilon \) is negative, note that \(-\epsilon\) is plotted. As is the case in Figure 3.4, it is usually convenient to think of the energy loss as a function of energy, rather than velocity. The usefulness of doing this will become evident in section 3.3.2, where an energy loss combined with a cross section (also as a function of projectile energy) will be used in defining the yield for a jet–clump reaction.

Jet ion velocities and average thermal electron velocities are compared in Figure 3.5. For typical model parameters (i.e., jet energies of 100 to 1000 A MeV and \( T_0 \) from 0.1 to 1.0) the two velocities are similar. If \( T_0 = 0.2 \) and the jet energy is anywhere in the above range, \( v_{\text{ion}} \) is initially greater than \( \bar{v}_e \), but, as the jet particles slow down, \( v_{\text{ion}} \) drops below \( \bar{v}_e \). Thus the ions are neither much faster nor much slower than the thermal electrons.

Unfortunately, no simple formalism exists to describe the energy loss when the electrons and the incident ions have comparable velocities. Therefore, we must choose between the two formulas given above. In the slow ion formula, the stopping comes from the small fraction of electrons in the Maxwell-Boltzmann distribution which have a velocity less than that of the incident ion (Post 1956). Increasing the ion velocity slightly (so that \( v_{\text{ion}} \) is still much less than \( \bar{v}_e \)) causes an increase in the energy loss because more of the thermally distributed electrons fall below the ion velocity.
Figure 3.4: A comparison of the energy loss for protons (in a) and alpha particles (in b). Three types of energy loss are shown in each panel. Atomic energy loss occurs when the stopping material consists of neutral atoms. For the values in this figure, the atomic stopping material is composed of 93% $^1$H and 7% $^4$He. In this case, the units of the energy loss are MeV/(atoms/cm$^2$), so that the “particles” referred to in the y-axis label are atoms. If the material is fully ionized, then the energy loss will be to the plasma electrons. The fast ion energy loss is applicable when the ions have a velocity much greater than the average thermal electron velocity, while the slow ion energy loss is for ions moving much slower than the thermal electrons. For all values of plasma energy loss, the units are MeV/(electrons/cm$^2$). The fast ion plasma energy loss depends on the electron density, which is set to $10^{18}$ particles/cm$^3$. The slow ion energy loss depends on the temperature, which is $T_9 = 0.2$ for the data plotted here. Also, a cross section involving the corresponding projectile is shown on each plot. Since the yields of the jet-clump reactions are proportional to the inverse of the energy loss, it is easy to see here the importance of choosing the right energy loss. Since $dE/dx$ is negative, the energy loss values plotted here actually represent $-\epsilon$. 

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Figure 3.5: Velocities for beam particles (solid curve) of various energies and average thermal velocities for electrons (dashed curve) over a range of typical clump temperatures.
However, if the ion velocity is increased further so that it approaches or exceeds $v_e$, the number of slow electrons (relative to $v_{ion}$) does not keep increasing as implied by the monotonic rise of equation 3.38. The Maxwell-Boltzmann distribution eventually turns over, and so the number of slow electrons simply cannot keep increasing. Thus the energy loss given by the slow ion formula is too large in the velocity regime where $v_{ion}$ and $v_e$ are comparable.

In the fast ion formula, the stopping comes from electrons which are assumed to be nearly at rest with respect to the incident ion. If, however, the velocities are comparable, the ion will already be slower than a significant fraction of the electrons in the high velocity end of the Maxwell-Boltzmann distribution. These electrons cannot contribute to the energy loss, which is then less than that given by the fast ion formula. Also possible when $v_{ion} \sim v_e$ is the temporary capture of electrons by the ion. Since this gives the ion a lower effective charge, the energy loss will be reduced even further. Therefore equation 3.37 is expected to be an upper limit for the energy loss in the case of similar ion and electron velocities.

As $v_{ion}$ approaches and drops below $v_e$, the fast ion formula gives an energy loss which is too high. Since the number of jet particles participating in jet-clump reactions is proportional to $1/\epsilon$, an incorrectly large value of $\epsilon$ decreases the quantities of product nuclei introduced by these reactions. We have developed a scheme for reducing the fast ion energy loss according to the fraction of electrons whose thermal velocities are actually below the ion velocity. The fraction of electrons with velocities
\( v_e \) below \( v_{\text{ion}} \) is given by

\[
\begin{align*}
  f_e &= \frac{\int_{0}^{p_{\text{cut}}} e^{-\sqrt{m_e c^4 + p^2 c^2} / kT} d^3p}{\int_{0}^{\infty} e^{-\sqrt{m_e c^4 + p^2 c^2} / kT} d^3p}.
\end{align*}
\]  

(3.42)

Here we are integrating the normalized, relativistic\(^7\) Maxwell-Boltzmann distribution up to momentum \( p_{\text{cut}} \), which is just the electron momentum corresponding to an electron with velocity \( v_{\text{ion}} \). Thus

\[
  p_{\text{cut}} c = \gamma \beta m_e c^2,
\]

(3.43)

with \( \beta = v_{\text{ion}} / c \), and \( \gamma \) is the usual Lorentz factor. In this way, the fast ion energy loss can be reduced according to how many of the thermal electrons are actually slower than the ion.

Figure 3.6 shows the resulting values for the reduced fast ion energy loss. Curve 1 represents the regular fast ion energy loss formula, and curve 5 is curve 1 times the fraction of electrons with velocities slower than the ion velocity. Curves 2 through 4 represent partial reductions of the fast ion formula. Curve 2 is constructed by reducing curve 1 just 50% of the way to curve 5, curve 3 is a 75% reduction, and curve 4 is 90% of the full reduction. Curve 6 is the slow ion energy loss, and it is interesting to note that the fully reduced fast ion energy loss (curve 5) has the same shape at low energies as the slow ion curve, although they still differ in magnitude by a factor of 2.

\(^7\)The relativistic formula provides only a small correction when the temperature is \( T_9 = 0.2 \), but at \( T_9 \) above 3, the correction becomes important.
Figure 3.6: Energy loss in MeV/(electrons/cm$^2$) for fast ions (1) and slow ions (6). Labels 2 through 5 refer to reduced fast ion energy loss curves. The method for generating these curves is given in the text. Basically, curve 5 is curve 1 multiplied by the fraction of thermal electrons whose velocities are below the ion velocity. Curves 2 through 4 are intermediate reductions (50%, 75%, and 90%, respectively) between 1 and 5.
The point in partially reducing the fast ion energy loss is to provide a mechanism which can lower $e$ without making it pathologically small at low energies. In practice, however, no jet-clump reactions occur below 20 MeV, since the threshold of all significant reactions is just above this energy. Thus the importance of an accurate energy loss value is diminished at very low energies.

The final technique we choose for the energy loss is that used in generating curve 4. This offers a significant reduction, but still avoids the drastic downturn at low energies. We do not make any further reductions to the energy loss to account for the partial capture of plasma electrons, and so the true energy loss could actually be lower than the values we end up using.

Using a reduced energy loss such as curve 4 only has an effect for jets with energies not much above 100 $A$ MeV. When the jet has an energy much higher than this, curve 4 and the regular fast ion energy loss are nearly identical for most of the relevant energy regime, and the resulting jet-clump reaction product yields are very similar for both curves.

Energy straggling is not important in our simulation. Straggling refers to the random fluctuations in energy loss for ions of very low energy. The energy at which this process becomes important is far below the thresholds for most of the jet-clump reactions and only causes tiny changes in the yields of reactions with no threshold. Straggling can also introduce uncertainties in the thickness necessary to stop an ion. These uncertainties are also negligible in our model, because the range of stopping
thicknesses due to the intrinsic energy distribution of the beam is much greater than any differences due to straggling. Therefore we ignore straggling.

**Effects of Mass Deposition**

The mass deposition primarily affects the density of the clump. In our model, we test three different density evolution scenarios. In the first scenario, we assume that the clump is strongly confined so that all the mass from the jet which is stopped in the clump remains trapped there throughout the simulation. The density as a function of time increases purely according to mass deposition from the jet. At late times, the density can become arbitrarily high in this case. Since the strength of the confinement is a function of complexities outside our model (hydrodynamic instabilities, viscosity, magnetic fields, etc.) we explore densities as high as $10^{23}$ particles/cm$^3$. This choice is partly biased by a knowledge of our results in this density regime, and so it may or may not be a legitimate upper limit.

The second option for the density evolution is to keep the density constant at its initial value. This is expected to occur for weakly confined clumps. In order for the density to stay constant, an amount of mass equal to that brought in by the jet must also leave the clump for every time step. All material which leaves the clump is assumed to have the same abundance concentrations as gas which remains in the clump.

A third scenario for the density evolution allows the density to increase as in the first mode, but only up to a maximum value, at which point the inflow and outflow
are balanced as in the second evolution mode. Since the maximum density for quasar clumps is not known, we treat it as a free parameter. Results for each of these three density evolution modes are presented in Chapter 4.

In addition to its effect on the clump density, the jet will also increase the momentum of the clump as high velocity material from the jet is absorbed by the clump gas. For intense jets and small clumps, the clump gas can be accelerated to velocities approaching that of the incident jet, which is relativistic. The velocity widths of emission lines from the BLR can be as high as 0.1c, which indicates that relativistic gas velocities are indeed possible in quasars. However, recent work on reverberation mapping (Korista et al. 1995) seems to indicate that the gas motion may not be radial, as would be the case for clumps accelerated away from the central region by the jet. Furthermore, clumps with large velocities would soon escape the innermost region of the quasar, in which case they are not likely to be able to sustain high temperatures. Therefore, if a large fraction of the clump mass is to come from the jet, then there also needs to be a mechanism for dissipating the jet momentum.

As a final note about the mass deposition, we discuss the situation where the clump is not thick enough to stop any of the primary jet. For very thin clumps, the jet will pass through the gas, only losing a fraction of its energy in the process. In this case, however, the collision products from jet-clump reactions may still be trapped in the clump. The reaction products have a substantially lower energy than the primary jet particles, because each product receives only a fraction of the projectile energy.

---

8 Recall that the Broad Line Region is so named because of the large velocity widths of the emission lines.
3.3.2 Jet–Clump Reactions

In addition to depositing its primordial material in the clump, the jet also introduces key nuclei via the jet–clump reactions. As the jet particles move through and are slowed down by the plasma electrons, they may also collide with clump nuclei. Compared to the thermal energies of nuclei in the clump, the incident energies of the jet particles are relatively high, and the cross sections for some reactions between jet nuclei and clump nuclei are also fairly high. Thus a substantial fraction of the jet particles can undergo jet–clump reactions. It is important to point out that the projectiles in the jet do not have a thermalized (i.e., Maxwell-Boltzmann) energy distribution. Once stopped, products of jet–clump reactions (as well as the jet particles

Also, most jet–clump reactions have a negative $Q$-value, which further reduces the kinetic energy available to the products. Therefore, the products could be stopped (via energy loss to clump electrons) even if the jet passes through. Then the clump would be enriched only in the product nuclei of the jet–clump reactions, and it is these products which give rise to the primary nucleosynthesis pathways in our model. However, in order for this type of selective deposition to occur, the density would need to be finely tuned to provide enough target material for reactions, but not too much material so that the jet can still penetrate the cloud. Further discussion and abundance results for this situation are given in Chapter 4, although we do mention here that the requirement of the relatively low and finely tuned density makes this an unlikely candidate for major contributions to metal production in quasars.
themselves) will be thermalized, and can participate in the thermal nucleosynthesis processes described earlier in Section 3.2.

As an example, if a 1000 A MeV jet of \(^1\)H particles strikes a hot \((T_g = 0.2)\) clump composed of primordial gas which is thick enough to stop the jet, then 10% of the protons in the jet will participate in the \(^4\)He(p,\(^3\)He)pn reaction. The introduction of such a large amount of \(^3\)He produced by this reaction will certainly affect the thermal nucleosynthesis in the clump.

Jet-clump reactions are classified into three different levels - primary, secondary, and tertiary - based on the source of the projectile for the reaction. Primary reactions occur between jet particles and clump nuclei. The reaction products of primary reactions will still have sufficient kinetic energy to penetrate further into the clump, and collisions between these particles and clump nuclei are the secondary reactions. Tertiary reactions occur as secondary reaction products strike nuclei in the clump. In practice, the tertiary reactions are not found to be a significant source of key nuclei, and since the tertiary products are so scarce, we do not consider any higher level reactions.

Jet particles and reactions are listed in Tables 3.5 and 3.6, respectively. Cross sections for the reactions are available in the literature, as indicated in Table 3.7. A selection of these cross sections is displayed in Figures 3.7 and 3.8.

Figure 3.8 also shows typical energy distributions of projectiles and products for each of the three different levels of jet-clump reactions. The panels in the first and third rows show the energy distribution for the projectile whose reaction cross section
is plotted in the corresponding column in the second row. The $^4$He in column 1 comes from the jet, and hence has a Gaussian distribution. In the upper panel, the jet has a mean energy of 1000 A MeV, and in the lower panel only 100 A MeV. For both cases, the standard deviation is 10% of the mean. The $^7$Be, $^{10}$B, and $^{13}$C (shown in columns 2, 3, and 4 respectively) are the products of the previous level reactions. The $^7$Be and $^{10}$B continue on in the clump and become the projectiles for the next level reaction. We do not consider Level 4 reactions, and so no cross section is shown which uses $^{13}$C as a projectile.

The relative amounts in each energy distribution are indicated inside the graphs. The $^4$He distribution is normalized so that the sum of all energy bins adds up to 1.0. Each subsequently higher level reaction converts only a small fraction of the projectiles into products. It is interesting to note that the $^7$Be produced by $^4$He($\alpha,n$)$^7$Be has a similar distribution whether the jet is 100 or 1000 A MeV. Since the cross section drops off exponentially above 50 MeV, not much of the yield for this reaction will occur above this energy. This also explains why the yield of the $^7$Be is so low for the higher energy beam. By the time the 1000 A MeV beam has been degraded in energy down to 200 MeV, most of the $^4$He nuclei have been destroyed by other level 1 reactions, most notably $^4$He(p, pn)$^3$He and $^4$He(p, 2p)$^3$H. Thus only a small fraction of the original $^4$He in the jet is left to participate in $^4$He($\alpha,n$)$^7$Be.
Table 3.5: All the particles which could be in the jet. Not every simulation includes all the particles since the more fragile nuclei could easily be destroyed in the pre-jet material.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>H</td>
<td>H</td>
<td>He</td>
<td>He</td>
</tr>
</tbody>
</table>

Figure 3.7: Selected cross sections for reactions between $^4$He in the jet and $^1$H in the clump. Other reactions appear in Figure 3.8. The x-axis is $^4$He energy in the lab frame, and the y-axis is the total cross section in millibarns ($1\text{ barn} = 10^{-24}\text{ cm}^2$). The number for each curve refers to a reaction index in Table 3.6. Much of these data are from Meyer (1970).
## Jet–Clump Reactions

<table>
<thead>
<tr>
<th>Index</th>
<th>Reaction Name</th>
<th>Reference Key</th>
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<tbody>
<tr>
<td>Level 1</td>
<td>(^4\text{He}(p,d)^3\text{He})</td>
<td>a, b, c, d, e, f</td>
</tr>
<tr>
<td>2</td>
<td>(^4\text{He}(p,pn)^3\text{He})</td>
<td>m</td>
</tr>
<tr>
<td>3</td>
<td>(^4\text{He}(p,pp)^3\text{H})</td>
<td>m</td>
</tr>
<tr>
<td>4</td>
<td>(^4\text{He}(p,2d)p)</td>
<td>m</td>
</tr>
<tr>
<td>5</td>
<td>(^4\text{He}(p,dn)2p)</td>
<td>m</td>
</tr>
<tr>
<td>6</td>
<td>(^4\text{He}(p,3p)2n)</td>
<td>m</td>
</tr>
<tr>
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<td>(p(\alpha,d)^3\text{He})</td>
<td>a, b, c, d, e, f</td>
</tr>
<tr>
<td>8</td>
<td>(p(\alpha, pn)^3\text{He})</td>
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<tr>
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<td>(p(\alpha, pp)^3\text{H})</td>
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<tr>
<td>11</td>
<td>(p(\alpha, dn)2p)</td>
<td>m</td>
</tr>
<tr>
<td>12</td>
<td>(p(\alpha, 3p)2n)</td>
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<tr>
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<td>i, j, k</td>
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<tr>
<td>14</td>
<td>(^4\text{He}(\alpha,p)^7\text{Li})</td>
<td>i, j, k</td>
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<td>Level 3</td>
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Table 3.6: All the reactions between jet particles and clump particles which we include in our simulation, grouped by projectile. The notation \(A(x,y)B\) indicates that \(A\) is the target and \(x\) is the projectile. \(B\) and \(y\) are the reaction products. All projectiles are either particles in the beam, or products of lower level jet–clump reactions. The target particle is always a nuclide in the gas clump. Many of the reactions are between \(^1\text{H}\) and \(^4\text{He}\). Since both of these nuclei exist as projectiles in the jet and as targets in the clump, each reaction between them is listed in both the \(^1\text{H}\) projectile section and in the \(^4\text{He}\) section. The reference keys indicate the literature sources (listed in Table 3.7) for the cross section data.
Figure 3.8: Energy distributions and cross sections for a sample of each different level of jet-clump reaction. All energies are in MeV. The top and bottom rows show the energy distributions resulting from a sequence of reactions in which a product of the previous reaction becomes the projectile for the next reaction. The reactions are initiated by the $^4\text{He}$ jet, which has a mean energy of 1000 A MeV in the first row and 100 A MeV in the third row. The number of particles present in each distribution, normalized to the total initial amount of $^4\text{He}$, is indicated within each panel. The temperature of the clump for both beam energies was $T_g=0.2$, and the 90% reduced fast ion energy loss formula was used in calculating the yields.
Table 3.7: References for the cross sections of jet-clump reactions. The letters are keyed to reactions in Table 3.6.

<table>
<thead>
<tr>
<th>Letter</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Bunch, Forster, &amp; Kim (1964)</td>
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<tr>
<td>b</td>
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</tr>
<tr>
<td>c</td>
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<td>d</td>
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<td>f</td>
<td>Bernas et al. (1970)</td>
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<tr>
<td>g</td>
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<tr>
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</tr>
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<td>j</td>
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<tr>
<td>k</td>
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</tr>
<tr>
<td>l</td>
<td>Spasskii, Teplov, &amp; Fateeva (1966)</td>
</tr>
<tr>
<td>m</td>
<td>Meyer (1970)</td>
</tr>
</tbody>
</table>

Jet–Clump Reactions with Monoenergetic Projectiles

Consider first a monoenergetic beam of particles passing through a very thin single component medium, as illustrated in Figure 3.9a. The number of nuclear reactions between the beam nuclei \( b \) and the target nuclei \( t \) is called the yield, \( y \), and is given by Mukhin (1987) as

\[
y = N_b N_t \sigma(E) dx.
\]  

(3.44)

As before, \( \sigma(E) \) is the nuclear cross section in cm\(^2\) for the reaction between a beam particle and a target particle as a function of \( E \), the lab energy of the beam. \( N_b \) is
Figure 3.9: Pictorial representation of thin and thick targets. In a, the target is thin enough that the incident particles do not lose any energy as they pass through the block. In b, the target is thick enough to slow or possibly stop the beam. In each case, the beam has $N_b$ particles, and the target has $N_t$ particles per cm$^3$.

the number of beam particles. $N_t$ is the number density per cm$^3$ of the target nuclei, and $dx$ is the thickness of the target in cm. We use a lower case $y$ for the yield to distinguish it from the mole fraction, which uses an upper case $Y$. This formula assumes that the beam particles do not lose a significant amount of energy over the distance $dx$, so that the cross section is evaluated only at the incident beam energy.

If the block of target material is thick enough to slow or stop the beam particles, as shown in Figure 3.9b, then 3.44 must be integrated over the thickness of the block.

$$y = \int_0^d N_b N_t \sigma(E) \, dx \quad (3.45)$$
The thickness $dx$ can be expressed as the amount of energy lost over a small distance divided by the energy loss per distance.

$$dx = \frac{dE}{\left(\frac{dE}{dx}(E)\right)}, \quad (3.46)$$

where $dE/dx$ is a form of the energy loss, and is a function of the energy. Substituting this into 3.45 gives

$$y = N_b N_i \int_{E_{in}}^{E_{out}} \frac{\sigma(E)}{\left(\frac{dE}{dx}\right)} dE. \quad (3.47)$$

The integration is now over the beam energy, which starts at $E_{in}$, the incident energy of the beam, and goes down to $E_{out}$, the final energy of the particles as they exit the target block. If the beam stops in the target material, then $E_{out} = 0$. Although the integral is from a high energy to a low energy, it is still positive because $dE/dx$ is negative.

$N_i$ is assumed constant and can be brought outside the integral. $N_b$ can be treated as constant only if the depletion of beam particles is a small fraction of the total. For now, we will assume that $N_i$ is essentially constant, but later we will remove this assumption.

In a single component atomic medium, the density of target atoms $N_i$ is also the atomic density, $n_a$, which is used in defining the atomic energy loss in equation 3.40. With the energy loss expressed as $\epsilon = (1/n_a) dE/dx = (1/N_i) dE/dx$, equation 3.47 becomes

$$y = N_i \int_{E_{in}}^{E_{out}} \frac{\sigma(E)}{\epsilon(E)} dE. \quad (3.48)$$

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If the stopping medium has more than one atomic component, or if the material is a plasma so that the stopping electrons are decoupled from the target particles, then the target density \( N_t \) is not the same as the stopping particle density, which we will call \( N_{\text{stop}} \). If the material is atomic, then \( N_{\text{stop}} \) is the total number density of all types of atoms. If the stopping medium is a plasma, \( N_{\text{stop}} \) is the total electron number density. In either case, \( N_t \) retains its original definition as the number density of just the target species. Since it is desirable to express the energy loss in units of MeV/(particles/cm\(^2\)) rather than MeV/cm, we re-write equation 3.47 as

\[
y = N_b N_t \int_{E_{\text{in}}}^{E_{\text{out}}} \frac{\sigma(E)}{N_{\text{stop}} \left( \frac{1}{N_{\text{stop}}} \frac{dE}{dx} \right)} dE.
\]  

(3.49)

Next we define the ratio of target nuclei to stopping particles as \( f_t = N_t/N_{\text{stop}} \), and then equation 3.49 can be written in a form which is useful for any type of energy loss.

\[
y = N_b f_t \int_{E_{\text{in}}}^{E_{\text{out}}} \frac{\sigma(E)}{\varepsilon(E)} dE
\]  

(3.50)

Of course, one must be careful to define the target fraction according to the correct abundance of stopping particles, and the proper energy loss formula must be chosen.

Equation 3.50 assumes that only a tiny fraction of the beam particles are lost to collisions with target nuclei. When this is true, then \( N_b \) is nearly constant and can justifiably be brought outside the integral, as we have done previously. For beams which are strongly depleted, however, the number of beam particles available for interacting with target nuclei will decrease as the beam penetrates the target material.
With initial number of beam particle expressed as $N_b^0$, the number of beam particles which remain in the beam at energy $E < E_{in}$ can be expressed as a function of the energy in the following way.

$$N_b(E) = N_b^0 \cdot S(E)$$

(3.51)

Here we introduce the concept of a survival fraction, $S(E)$, which accounts for all the beam particles lost to nuclear reactions as the beam degrades in energy from $E_{in}$, its original, incident value, down to any lower energy $E$. Since all beam particles are present at the highest beam energy, $S(E)$ at $E = E_{in}$ is 1. At energies $E < E_{in}$, the survival fraction decreases as more and more beam particles are destroyed in collisions with target nuclei. The number of beam particles as a function of energy can be written as

$$N_b(E) = N_b^0 - \int_{E_{in}}^{E} N_b(E') \frac{\sum_{m} \sigma_m(E') (f_t)_m}{\epsilon(E')} dE'.$$

(3.52)

In words, this equation says that the number of beam particles surviving down to energy $E$ equals the initial amount of particles minus the total number of destruction reactions between the incident energy $E_{in}$ and the current energy, $E$. Thus the integral is from $E_{in}$ down to $E$, and not all the way down to $E_{out}$ as in the yield calculation. Also, to properly describe the depletion of the beam, all reactions which use the beam particle as a projectile (i.e. not just the one for which the yield is desired) must be included as destruction processes. The sum over $m$ thus accounts for the cross sections $\sigma_m$ of all destruction reactions $m$. Since each of these reactions may utilize a different target nuclide, the target fraction $(f_t)_m$ for each is also included inside the summation.
If \( N_b(E) \) under the integral in equation 3.52 is replaced with equation 3.51, \( N_b^0 \) can be factored out of each term, giving the equation for \( S(E) \).

\[
S(E) = 1 - \int_{E_{in}}^{E} S(E') \frac{\sum_m \sigma_m(E')(f_t)_m}{\epsilon(E')} \, dE'
\]

(3.53)

Formulas of a recursive nature such as 3.53 are known as Volterra equations, and can be solved by the standard numerical techniques described in Press et al. (1992).

Figure 3.10 depicts the survival fractions for beams of \(^1\)H and \(^4\)He at 1000 Am\(\text{eV}\) incident on a thick clump of primordial material at a temperature of \(T_g = 0.2\). The best way to interpret the graph is from right to left. All the beam is present initially at the incident energy. As the particles are slowed down by energy loss to the plasma electrons, many participate in nuclear collisions and are removed from the jet. By the time the beam is stopped, only 70% of the protons remain, and the alpha particles are more than 99% depleted. Ignoring the loss of beam particles to previous reactions would seriously overestimate the yield in this case.

The final form for the yield of a jet–clump reaction \( k \) is then

\[
y_k = N_b(f_t)_k \int_{E_{in}}^{E_{out}} S(E) \frac{\sigma_k(E)}{\epsilon} \, dE.
\]

(3.54)

However, this equation is not used in practice, because the process of calculating the survival fraction in the presence of several destruction reactions can also be used to obtain the yield for each of the destruction reactions. If the survival fraction is to be calculated for a discrete set of energy points, then at each point, there will be contributions to the beam particle destruction due to several different reactions. The \( \sigma_m \) for each of these reactions appears inside the sum in equation 3.53. The fraction
Figure 3.10: The survival fractions for $^1$H and $^4$He particles impinging on a clump of primordial gas (93% $^1$H and 7% $^4$He, by number) at $T_9$ of 0.2. The clump is thick enough to stop the jet. The particles start at 1000 $\text{A}\text{MeV}$, which is at the far right of each plot. As the particles lose energy in the clump, (and hence move to the left along the curves shown) some will participate in jet-clump reactions and thus be removed from the jet. At energies below all reaction thresholds, the survival fractions do not change, since no destruction reactions can occur at these low energies. The lowest threshold for $^1$H projectiles is 24 MeV, and for $^4$He it is 40 MeV.
of the destruction coming from an individual reaction \( k \) is thus

\[
\delta_k(E) = \frac{\sigma_k(E)(f_1)_k}{\sum_m \sigma_m(E)(f_1)_m}.
\] (3.55)

In order to refer to it later, we call \( \delta_k(E) \) the fractional destruction.

Once \( S(E) \) has been calculated, differences in the survival fraction between two energies \( E_2 \) and \( E_1 \) (\( E_2 > E_1 \)) can be used to indicate the total number of jet particle destruction reactions occurring between \( E_2 \) and \( E_1 \).

\[
dS(E_2, E_1) = S(E_2) - S(E_1)
\] (3.56)

As a technical note, we point out that the adjacent values of \( S(E) \) are often very nearly equal. Since computers lose a significant amount of accuracy when two such numbers are subtracted, we use a mathematically equivalent, numerically sensitive approach for finding each \( dS \) which involves some of the intermediate values used in finding each \( S(E) \).

The final expression for the yield of reaction \( k \) between \( E_2 \) and \( E_1 \) is just the total number of destruction reactions in this energy interval times the fractional destruction for reaction \( k \) in the interval.

\[
y_k(\text{between } E_2 \text{ and } E_1) = \delta_k(E_1) \, dS(E_2, E_1)
\] (3.57)

The cross sections inside \( \delta_k(E) \) are evaluated at \( E_1 \), because this is also where they are evaluated in the process of finding the survival fraction values.
Calculational method for beams with an energy distribution

Having described the essence of the yield calculation for a monoenergetic jet, we now proceed to explain some further steps which are needed if the jet is to have an energy distribution. We also point out that products of jet-clump reactions will be naturally distributed in energy even if the jet is monoenergetic. If these products serve as projectiles for higher level reactions, then our model must include some machinery for computing yields due to projectiles which have a spread in energy. To a large degree, the focus of the techniques described below is to construct an approach which is computationally efficient.

The energy distribution of a jet particle species or a jet-clump reaction product is represented as a set of discrete energies. For an energy distribution consisting of components \( i = 1, 2, \ldots, N \), the incident and final energies of component \( i \) are \( E_{\text{in}}(i) \) and \( E_{\text{out}}(i) \), and each component contains \( n_i \) particles. The expression for the yield of reaction \( k \) in this case is

\[
y_k = n_1 \int_{E_{\text{in}}(1)}^{E_{\text{out}}(1)} S_1(E') \frac{\sigma_k(E')(f_i)_k}{\epsilon(E')} \, dE' + n_2 \int_{E_{\text{in}}(2)}^{E_{\text{out}}(2)} S_2(E') \frac{\sigma_k(E')(f_i)_k}{\epsilon(E')} \, dE' + \cdots + n_N \int_{E_{\text{in}}(N)}^{E_{\text{out}}(N)} S_N(E') \frac{\sigma_k(E')(f_i)_k}{\epsilon(E')} \, dE'.
\]

(3.58)

Although the techniques of the previous section on monoenergetic beams could be applied to calculate the yield for each of these integrals, this approach would represent
a tremendous inefficiency and would take an unacceptably long time to calculate. Many of the integrals in equation 3.58 are likely to span overlapping regions of energy, a fact which can be exploited to speed up the calculation. As expected, the cost for increasing the speed of a calculation is a decrease in simplicity.

The first task is to set up the initial energy distribution by determining the number of particles $n_i$ and the incident energy $E_{in}(i)$ for each component $i$. Particles in the beam are given a Gaussian distribution according to the desired mean and standard deviation for a given execution of the simulation. Finding the energy distribution for reaction products is more complicated, and the process for doing this will be presented shortly. For now, we will assume that the $E_{in}(i)$ values for products which serve as projectiles are known.

Once the $E_{in}$'s are set, the next task is to find each corresponding $E_{out}(i)$, the energy of component $i$ after exiting the clump. For jet particles, an energy loss calculation is performed using each $E_{in}(i)$ as the initial energy. The thickness traversed by each component is the entire thickness of the clump. Jet-clump reaction products, however, are not all created at the same depth in the clump, and so each may see a different stopping thickness. Therefore, the $E_{out}$'s for these products are determined somewhat differently than for jet particles. First of all, if the projectiles which initiated a jet-clump reaction are all stopped in the clump, then all of the products for that reaction are assumed to be stopped as well. But if at least some of the initiating projectiles completely penetrate the clump, some of the products may also escape. Here we assume that the products of each higher level reaction see $1/2$ as much of
the clump as the previous level. Jet particles see the entire clump. Level 1 products see 1/2 of the clump, level 2 products 1/4\textsuperscript{th}, and level 3 products 1/8\textsuperscript{th}. Using the appropriate thickness, an energy loss calculation can be done to find $E_{\text{out}(i)}$ for each component of the product's energy distribution. Recall that this product is to be used as a projectile for a higher level reaction.

The $E_{\text{out}(i)}$ values are used for determining how much of the incident particles are stopped in the clump. If a component is stopped in the clump, then $E_{\text{out}(i)} = 0$.

As an example, consider the $^7\text{Be}$ projectile in the level 2 reaction $^4\text{He}(^7\text{Be, p})^9\text{B}$. Let us assume for now that the $E_{\text{in}}$'s for the $^7\text{Be}$ are set, although we have yet to demonstrate how this is done. The source of the $^7\text{Be}$ is the level 1 beam reaction $^4\text{He}(\alpha, n)^7\text{Be}$, which is initiated by the $^4\text{He}$ jet particle. If all the $^4\text{He}$ in the jet is stopped by the clump, then we assume that the reaction products, including the $^7\text{Be}$, are also trapped in the clump. Therefore all the $E_{\text{out}}$'s for $^7\text{Be}$ should be set to zero. If, however, at least some of the $^4\text{He}$ passes through the clump, then the thickness used to determine the $E_{\text{out}}$'s for $^7\text{Be}$ will be one half of the total clump thickness. For most cases, we use a thick clump capable of stopping all of the jet material, in which case all the $E_{\text{out}}$'s are zero.

Given a complete set of $E_{\text{in}(i)}$ and $E_{\text{out}(i)}$, the next step is to calculate the survival fraction of the projectile based on all its destruction reactions. This is also done at discrete, evenly spaced energies $E_y(j)$ ranging from the highest $E_{\text{in}(i)}$ down to the lowest $E_{\text{out}(i)}$. These energies $E_y(j)$ will in general have a different spacing than the $E_{\text{in}(i)}$. According to equation 3.57, the yield which occurs between any two adjacent
energies $E_y(j+1)$ and $E_y(j)$ is proportional to $dS(E_y(j+1), E_y(j))$. Thus the region between successive values $E_y(j)$ and $E_y(j+1)$ is referred to as the yield interval $j$.

At the bottom of Figure 3.13d is an example of the spacing of a set of yield intervals with respect to an initial and final energy distribution. The full explanation of Figure 3.13 will be given below. Since the jet in part d of the figure is stopped in the clump, the yield intervals extend down to zero energy. If the jet passed through the clump as in a or b, then the yield intervals would only need to go to the lowest energy of the $E_{out}$ distribution.

At the lower energy of each yield interval (the same energies where the survival fraction is calculated), the fractional destruction $\delta_k(E)$ (defined in equation 3.55) is also found for each of the destruction reactions. These values will be used later for finding the fraction of the yield in each yield interval which comes from each reaction.

The survival fraction $S(E)$ for a single energy beam is obtained by integrating the projectile losses from the highest energy $E_{in}$ down to $E$. and so it would appear that since each discrete energy component has a different $E_{in}(i)$, a separate survival fraction function needs to be calculated for each. This is indeed true, but the $S(E)$ for component $i$, let us call it $S_i(E)$, is trivially related to $S_N(E)$ (the survival fraction of the highest energy component) by a simple renormalization. Consider a beam which starts at energy $E_N$ and passes though energy $E_i$, as shown in figure 3.11. The number of beam particles present at any energy $E < E_i$ can be calculated based on the survival fraction $S_N(E)$ starting at $E_{in} = E_N$.

$$N_b(E) = N_b S_N(E)$$ (3.59)
Figure 3.11: The survival fraction at different energies. If a survival fraction based on an input energy below $E_N$ is desired, simply renormalize the survival fraction based on the highest energy with a factor $1/S(E_i)$, as described in the text.

It can also be obtained with a survival fraction $S_i(E)$ which is calculated starting from $E_{in} = E_i$.

\[ N_b(S) = \{\text{number of particles at } E_i\} \quad S_i(E) = \{N_b S_N(E_i)\} \quad S_i(E) \] (3.60)

Since the number of particles at energy $E$ must be the same regardless of the starting point for the survival fraction calculation (i.e., equating the right hand sides of 3.59 and 3.60).

\[ N_b S_N(E) = \{N_b S_N(E_i)\} \quad S_i(E), \] (3.61)

and thus

\[ S_i(E) = \frac{S_N(E)}{S_N(E_i)}, \] (3.62)
Therefore it is only necessary to compute the survival fraction once for the highest energy component of the jet, and then \( S_i(E) \) for the other components can be found via the renormalization given in equation 3.62. For simplicity, \( S(E) \) will refer to the highest energy survival fraction so that

\[
S_i(E) = \frac{S(E)}{S(E_{in}(i))}.
\]  

(3.63)

Renormalizing all the survival fractions in 3.58 according to 3.63 gives

\[
y_k = \sum_i^N \frac{n_i}{S(E_{in}(i))} \int_{E_{in}(i)}^{E_{out}(i)} S(E') \frac{\sigma_k(E')(f_i)_k}{\epsilon(E')} dE'.
\]  

(3.64)

Next, we define the effective amount \( n'_i \) as the amount \( n_i \) associated with component \( i \) divided by the appropriate survival fraction renormalization term.

\[
n'_i = \frac{n_i}{S(E_{in}(i))}.
\]  

(3.65)

This allows equation 3.64 to be re-written as

\[
y_k = \sum_i^N n'_i \int_{E_{in}(i)}^{E_{out}(i)} S(E') \frac{\sigma_k(E')(f_i)_k}{\epsilon(E')} dE'.
\]  

(3.66)

Since each integral in equation 3.66 has the same integrand and many of the integrals will overlap in energy, equation 3.66 can be recast in terms of integrals over the evenly spaced yield interval energies.

\[
y_k = \sum_j^{N_y} n_j^{thru} \int_{E_y(j)}^{E_y(j+1)} S(E') \frac{\sigma_k(E')(f_i)_k}{\epsilon(E')} dE'.
\]  

(3.67)

The \( n_j^{thru} \) are then sums of various \( n'_i \) values, according to which pairs of \( E_{in}(i) \) and \( E_{out}(i) \) contribute to each yield interval. Since yield interval \( j \) is bounded by \( E_y(j) \)
Figure 3.12: The ranges for $E_{in}(i)$ and $E_{out}(i)$ which will contribute to yield interval $j$. In order for the particles in component $i$ to contribute to yield interval $j$, they must "pass through" at least some portion of the yield interval. This will happen if $E_{in}(i)$ is above the lower energy boundary of the interval, or $E_{out}(i)$ is below the upper energy. $E_{in}(i)$ and $E_{out}(i)$ could either end up both inside the interval, both outside, or just one of them inside. In any case, $E_{in}(i)$ must be greater than $E_{out}(i)$.

below and $E_{y}(j + 1)$ above, and recalling that $E_{in}(i) > E_{out}(i)$. the $n_{j}^{\text{thru}}$ of yield interval $j$ will receive a contribution from the beam component $i$ if

$$E_{in}(i) > E_{y}(j) \quad \text{and} \quad E_{out}(i) < E_{y}(j + 1).$$

Figure 3.12 helps illustrate the values of $E_{in}(i)$ and $E_{out}(i)$ which will contribute to yield interval $j$.

It is easier to think about re-distributing the integrals from equation 3.66 to equation 3.67 in terms of the "flow" of groups of $n_{i}^{j}$ particles from $E_{in}(i)$ down to $E_{out}(i)$. A jet component $i$ makes a contribution to a yield interval $j$ if particles $n_{i}^{j}$ with incident energy $E_{in}(i)$ pass through interval $j$ as they degrade in energy to $E_{out}(i)$. If the particles pass completely through yield interval $j$ (i.e., $E_{out}(i) \leq E_{y}(j)$ and $E_{in}(i) \geq E_{y}(j + 1)$), then $n_{j}^{\text{thru}}$ receives the full contribution $n_{i}^{j}$. If, however, the
flow of component $i$ from $E_{\text{in}}(i)$ to $E_{\text{out}}(i)$ begins or ends in the middle of yield interval $j$, then the contribution to $n_j^{\text{thru}}$ will be a fraction of $n_i'$ according to the fraction of the interval traversed. Thus finding the contributions to each yield interval $j$ can be thought of as finding the total amount of particles from all combinations of $E_{\text{in}}(i)$ and $E_{\text{out}}(i)$ which descend through $j$.

Figure 3.13 helps illustrate the concept of the yield intervals and the quantities $n_j^{\text{thru}}$. The figure consists of four panels, each one showing $E_{\text{in}}$ (the solid rightmost Gaussian curve) and $E_{\text{out}}$ (the dashed, left-most curve) distributions for a jet impinging on successively thicker clumps. In a, the clump is very thin, so that the jet particles lose only a small fraction of their energy as they pass through the entire clump. In b, the jet is substantially degraded in energy, but still makes it all the way through the clump. In c, a portion of the jet is stopped in the clump, and in d, all the particles have a final energy of zero, indicating that they have stopped within the clump. The histogram bar at zero energy in part d represents the accumulation of all the $E_{\text{out}}$ components at zero energy.

The discrete energies used in the $E_{\text{in}}$ and $E_{\text{out}}$ distributions are shown as vertical lines under the continuous curves. Each vertical line in the $E_{\text{in}}$ distribution has a corresponding line in the $E_{\text{out}}$ distribution which indicates the final energy for that component. To keep the plots from looking too cluttered, only 1 of every 7 discrete energies is actually shown. In reality, each distribution has 100 energy points. The amounts in the distribution are normalized so that the maximum amount is 1.0.
Figure 3.13: Different possibilities for the relative locations of the (normalized) $E_{\text{in}}$ and $E_{\text{out}}$ distributions. See the text for a full explanation.
The arrangement of the yield intervals is shown only for the lowest panel. The energy boundaries for 1 out of every 20 (also done to avoid a cluttered look) intervals is shown as a vertical line. The yield intervals are much more finely spaced than the particle energy distributions, because the yield for some jet-clump reactions may occur in a relatively small width of energy space. If the yield intervals are too coarse, the yield from a narrow energy space reaction would be poorly described. One such reaction is \(^4\text{He}(\alpha,n)^7\text{Be} \), whose yield occurs mostly below 100 MeV for the \(^4\text{He} \) projectile. If the \(^4\text{He} \) in the jet starts at 4000 MeV and is stopped in the clump, a survival fraction with only 100 points would only contain two points below 100 MeV! We typically use survival fractions with 1000 points, as was done in generating the data for these figures.

The solid line in each panel which spans the energy regime of both distributions gives \(n^{\text{thru}}\). normalized to 0.9 to avoid confusion with the energy distribution lines. As explained above, each \(n^{\text{thru}}_j\) records the number of particles which flow through yield interval \(j\) as all components of the \(E_{in}\) distribution degrade in energy to their corresponding values in the \(E_{out}\) distribution.

Finally, the yield of reaction \(k\) within yield interval \(j\) is

\[
y_k(j) = n^{\text{thru}}_j dS(E_y(j), E_y(j + 1)) \delta_k(E_y(j)).
\]  

(3.69)

The difference between this equation and 3.57, the monoenergetic yield equation, is the factor \(n^{\text{thru}}_j\) to account for the different components of the beam which contribute to the yield between the energies \(E_y(j)\) and \(E_y(j + 1)\). Recall that \(\delta_k(E)\) as defined
in equation 3.55 gives the fraction of the total yield at energy $E$ caused by reactions $k$.

The total yield for a given reaction is found by summing the contributions from each yield interval.

$$y_k = \sum y_k(j)$$

(3.70)

The total yield of all destruction reactions $k$ is then used to determine how much of the incident beam survives to be considered for mass deposition in the clump.

Only one more aspect of the yield calculation remains. If any of the destruction reactions $k$ has a product particle which is used as a projectile in a higher level reaction, then the energy distribution of that reaction product needs to be found. The yield intervals are very helpful at this point, because they record how much of the yield occurs at each possible reaction energy. The products which arise from the reactions in each yield interval $j$ are distributed in energy according to the kinematics at that reaction energy (see Marion & Young (1968) and Baldin, Goldonskiï, & Rozental' (1961) for further detailed information on kinematics). The lower energy of the interval is used for the reaction energy.

Angular distributions are not available for all of the jet-clump reactions we use. Therefore the angular distribution of each product is approximated with a linear function in $\theta$ which extends up to $\theta_{\text{max}}$, the maximum angle allowed by the kinematics for a particular product. The normalization of the angular distribution at each yield interval energy is set so give the total yield at the appropriate yield interval.
The angular distributions in the lab frame are used to determine how much of each product goes into each allowed lab angle, up to the maximum allowed. We only use the angle of the reaction products for determining energies. Just as we do not keep track of the position within the clump at which the products were created, we do not keep track of the angle at which they are traveling.

Using the lowest energy of the yield interval and using a linear angular distribution will give product energies which are slightly lower than their true values. Subsequent yield calculations based on these lower energies are only slightly affected, since the average projectile energy may only drop by a few MeV as a result of our approximations.

Deposition of jet–clump reaction products.

In the same way that jet particles are slowed and possibly stopped in the clump, the products of jet–clump reactions can be deposited in the clump. Some details of this process are described above in the discussion of the procedure for finding the $E_{\text{out}}$'s, but we also mention it here for clarity. In principle, it would be possible to determine the precise location in the clump at which the various reaction products are created. However, in order to simplify the situation we use a clump which consists of a single region. Thus our concern is not where the particles stop, but just whether or not they are stopped in the clump.

As described above, the jet particles are stopped in the clump according to their energy loss through the entire thickness of the clump. Reaction products are assumed
to stop in the clump if the projectile which created those products is also stopped in
the clump. If the projectile is not stopped, then the stopping of the reaction products
is calculated based on the energy loss, as is done for the jet particles. The only
difference is that the products of each higher level reaction are assumed to go through
successively smaller and smaller fractions of the clump. Primary reaction products are
given one half of the clump thickness in which to stop, secondary reaction products
one fourth, and tertiary products one eighth.

An alternate method of determining the stopping in thin clumps is used for reac­
tions which create three or more products. Although the kinematics routine we use is
relativistically correct, it can only handle two particles in the exit channel. Since our
code therefore cannot calculate exact energy distributions for the products of these
many-product reactions, we employ the following approximation. Exact energy dis­
tributions can be calculated for two-product reactions, and, based on the energy loss
of these products, the fraction of each product which gets stopped in the clump can be
determined. We then assume that the same fraction of products from many-product
reactions is also stopped. Each projectile has only one two-product destruction reac­
tion, and so we use the fraction of the lighter product particle in figuring the deposition
of all other three-product reactions which have the same projectile. The lower en­
ergy per product which is expected for three product reactions implies that they will
actually be more readily stopped than products of two-product reactions. Therefore,
our procedure underestimates the deposition from many-product reactions. However,
this type of deposition only occurs when the clump is not thick enough to stop all
of the jet projectiles. As mentioned before, this situation plays a limited role in the generation of quasar metals. Therefore we do not deem it necessary to use a more complicated or accurate approach.

**Linking the Jet and the Thermonuclear Reactions**

Deposition of jet particles and jet-clump reaction products is accomplished by inserting additional terms into the abundance evolution equation of each nuclide introduced by the jet. These terms are like source terms, in that they represent the appearance of material in the clump. Each target species in the clump which is destroyed by the jet also must also receive a term in its equation of abundance versus time in order to account for its disappearance via a jet-clump reactions.

In our single zone approach, we assume that the jet material is distributed evenly throughout the entire clump volume. Therefore the value of the terms representing the deposition depend not only on the mass input rate of the jet, but also on the the clump volume. Suppose reaction $k$ produces a nuclide $i$. The yield of the reaction is $y_k$, and the number abundance of $i$ is $n_i$. The rate equation for $i$ will then contain a term

$$\frac{dn_i}{dt} = \frac{y_k}{\text{clump volume}}.$$  \hspace{1cm} (3.71)

Converting the number abundance to a mole fraction via $n_i = Y_i \rho N_A$, this becomes

$$\frac{dY_i}{dt} = \frac{y_k}{\text{clump volume}} \frac{1}{\rho N_A}.$$  \hspace{1cm} (3.72)
which is compatible with the mole fraction abundance equations presented in Section 3.2.3. With the inclusion of terms for the appearance of jet particles and jet-clump reaction products, as well as terms for the destruction of target nuclei, baryon number conservation is retained.

3.4 Summary

The jet clump interaction model incorporates the processes which are expected to occur as a high energy beam of particles strikes a hot, dense clump of gas. The mass deposition by the jet can significantly increase the density of the clump, which in turn boosts the rate of thermonuclear nucleosynthesis. Also, the collision of energetic jet particles with clump nuclei can initiate reactions which generate key nuclei. These nuclei boost the thermonuclear processes by providing a way to jump the mass 5 and mass 8 stability gaps. Abundance calculations for various temperatures, jet masses, and final clump densities are given in the next chapter.
CHAPTER 4

Results

In this chapter, we describe jet-clump metal production under a variety of conditions. Quantities representing the state of the quasar environment are parameterized to enable a systematic search of all possible scenarios. The full range for each of the variable parameters is studied. In some cases, regions of parameter space can be characterized based on known trends in the results.

The chapter is organized around three different clump sizes which we refer to as large, medium, and small. For each of these sizes, we show first the abundance evolution for a sample set of parameters. Then we describe the effects on the metal production caused by variations in each of the parameters other than clump size.

Scenarios in which the density remains constant are treated separately, as are cases where the clump is initially too thin to stop the jet. The metal production for each of these cases is very limited.

Interspersed throughout the chapter are comments on the plausibility of different parameter combinations. Further analysis concerning the results of our parameter space search is given in the concluding chapter.
4.1 Reminder of the Parameters

Before diving into the output of simulation runs, we first provide a reminder of the parameters involved in the model.

4.1.1 Fixed Parameters

Much of the physics of the jet clump model is determined and does not need to be parameterized. In particular, the functions describing the thermonuclear reaction rates and the cross sections of jet-clump reactions are well understood. These do not change in any of our simulations. For the energy loss of the jet ions in the clump plasma, a precise characterization is not available. Therefore we utilize an approximation to the maximum energy loss via a procedure described in section 3.3.1 of the previous chapter. The technique used to generate curve 4 in Figure 3.6 is used to find the ion energy loss for all parameter combinations described here.

4.1.2 Variable Parameters

The variable physics inputs of the jet-clump model include characteristics of quasar gas and jets which are known to vary or else are not tightly constrained at this time. Table 4.1 indicates the various parameters and the symbols by which we refer to them throughout this chapter. The table also gives a range of values explored for each parameter.
<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Symbol</th>
<th>Range Explored</th>
<th>Typical Step Size</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>$T_g$</td>
<td>0.1 to 3.0</td>
<td>+0.2</td>
<td>billion K</td>
</tr>
<tr>
<td>Initial Particle Density</td>
<td>$\rho_{Ni}$</td>
<td>$10^{11}$ to $10^{18}$</td>
<td>$\times 10^1$</td>
<td>$1/cm^3$</td>
</tr>
<tr>
<td>Final Particle Density</td>
<td>$\rho_{Nf}$</td>
<td>$10^{11}$ to $10^{23}$</td>
<td>$\times 10^1$</td>
<td>$1/cm^3$</td>
</tr>
<tr>
<td>Clump Diameter</td>
<td>$d$</td>
<td>$10^{11}$ to $10^{13}$</td>
<td>$\times 10^1$</td>
<td>cm</td>
</tr>
<tr>
<td>Clump Length</td>
<td>$l$</td>
<td>$10^{11}$ to $10^{13}$</td>
<td>$\times 10^1$</td>
<td>cm</td>
</tr>
<tr>
<td>Jet Mass Rate</td>
<td>$\dot{M}_\odot$</td>
<td>0.1 to 10</td>
<td>$\times 10^1$</td>
<td>$M_\odot/yr$</td>
</tr>
<tr>
<td>Mean Jet Energy</td>
<td>$E_{\mu}$</td>
<td>100 to 1000</td>
<td>+250</td>
<td>MeV/amu</td>
</tr>
<tr>
<td>Width of Jet Energy</td>
<td>$E_{\sigma}$</td>
<td>10% of $E_{\mu}$</td>
<td>—</td>
<td>MeV/amu</td>
</tr>
</tbody>
</table>

Table 4.1: Variable physics parameters and their ranges in the jet-clump interaction model. The fourth column indicates the typical step size between two adjacent parameter values. The presence of a plus sign (+) indicates that the subsequent parameter values are obtained by simply adding the step size to the previous value. The times symbol ($\times$) indicates that subsequent parameter values contain an additional factor of the step size.

The values of $\rho_{Ni}$ and $\rho_{Nf}$ (the initial and final particle densities) together determine the density evolution mode. The three possible density evolution modes are described in the following ways: 1. the density remains constant. 2. the density keeps increasing, or 3. the density increases up to a maximum value. The first of these is represented by $\rho_{Ni} = \rho_{Nf}$. For the second mode, $\rho_{Nf}$ is set to infinity. However, the density does not approach infinity in this case. It is better to think of $\rho_{Nf}$ as a ceiling for the density, and so $\rho_{Nf} = \infty$ is simply an indicator that there is no ceiling on the allowed density growth. The actual density reached in this case depends on the rate of mass deposition from the jet. In the last of these three modes, $\rho_{Nf}$ is larger than $\rho_{Ni}$, but finite. The density as a function of time starts at $\rho_{Ni}$. Once the density
climbs to $\rho_{Nf}$, a balance is maintained between the particles flowing in and out of the clump. All material leaving the clump is assumed to have the same concentrations as material which stays in the clump.

### 4.1.3 Explaining the Ranges of the Parameters

Several of our parameter choices are obtained from the literature. As mentioned in Chapter 3, gas temperatures in the central quasar environment may reach $T_g$ around 1.0. The range $T_g = 0.2$ to 3.0 allows us to explore the possible effects of different temperatures on the nucleosynthesis. Gas densities quoted in Chapter 3 extend up to $10^{18}$ particles/cm$^3$. We consider initial densities from $10^{11}$ particles/cm$^3$ (the supposed density of BLR gas) up to $10^{18}$ particles/cm$^3$. The final density obtainable due to mass deposition from the jet is unknown, simply because the gas confinement mechanism in quasars has yet to be fully explored. For the sake of completeness, we consider final densities up to $10^{23}$ particles/cm$^3$. An explanation of the ranges used for the jet mass and jet energy is given in Chapter 3, section 3.1.2.

In order to estimate an appropriate clump size, first consider the clouds in the BLR, which have an approximate diameter of 400 $R_\odot$, or $3 \times 10^{13}$ cm. ($1R_\odot$ is 1 solar radius, which is $7 \times 10^{10}$ cm.) Also, recall that NLR clouds exists further from the central source and are larger than their BLR counterparts. Therefore cloud sizes increase for greater distances from the central source. Since the clumps in our model are expected to exist closer to the central source than the BLR, they might also be expected to be smaller than $3 \times 10^{13}$ cm.
The size of the black hole itself should also be considered in estimating the clump size. As given in Chapter 1, the Schwarzschild radius of the central black hole is approximately

\[ R_s = 3 \times 10^{12} \frac{M}{M_\odot} \text{ cm.} \quad (4.1) \]

\( M \) is the black hole mass in \( M_\odot \), and \( M_\odot \) is \( 10^7 \) M\( \odot \). Quasars typically contain a black hole of about \( 10^6 \) to \( 10^9 \) solar masses. Assuming clump sizes comparable to \( R_s \) yields a range of values \( 10^{11} \) to \( 10^{14} \) cm for the clump size scale.

### 4.1.4 Parameter Search Method

The number of parameter combinations in Table 4.1 is quite large. With the ranges and step sizes shown in the table, there are over \( 10^5 \) different points in parameter space. Fortunately, this number can be reduced somewhat due to the dependencies among the parameters. Also, general trends in the results allow some ranges of the parameter values to be characterized without a detailed examination.

One simple reduction involves equating \( d \) and \( l \), the clump diameter and length. This is roughly similar to saying that the cylindrical clump is not too far from spherical in shape.

Recall that the clump volume \( \frac{2\pi}{3} d^3 = \frac{\pi}{4} d^2 l \) for \( d = l \) and the total mass input rate of the jet \( \dot{M}_\odot \) together define \( \dot{M} \), the mass input rate per cm\(^2\). Since we use a single zone model, the nucleosynthesis is only sensitive to \( \dot{M} \) and any combination of \( d \) and \( \dot{M}_\odot \) which give the same \( \dot{M} \) will also give the same abundance evolution pattern.
Figure 4.1: The parameter space for combinations of $d$ and $\dot{M}_\odot$. Allowed values of these two quantities are restricted to points on or within the central box. With all other parameters fixed, the nucleosynthesis is affected only by the mass deposition per cm$^3$, $\dot{M} = \dot{M}_\odot/(\frac{\pi}{4} d^2 l)$. If $d$ is set equal to $l$, and $l$ is greater than the range of all jet particles so that the jet is completely stopped in the clump, then the relative abundances obtained for a given simulation will be the same along curves of constant $\dot{M}_\odot/d^3$. Nine possible values for $\dot{M}$ are shown as slanted lines. The abundance evolution for each of these nine values is explored based on $d$ and $\dot{M}_\odot$ values at the points indicated with small circles.
per cm$^3$ in the clump. Of course different total volumes and masses are affected for different choices of $\dot{M}_\odot$ and $d$.

Equivalent combinations of $\dot{M}_\odot$ and $d$ are illustrated in Figure 4.1. The box in the middle of the figure indicates the boundaries within which are the allowed choices of the two parameters. Note that we do not include clump sizes of $10^{14}$ cm for reasons given in section 4.2.3. Each angled line corresponds to a unique value of $\dot{M}$, the mass input rate per cm$^3$. The value of $\dot{M}_\odot/d^3$ on the lower, rightmost of these lines is $10/(10^{11})^3 = 10^{-32}$. Each successive line encountered when moving up and to the left represents an $\dot{M}$ which is a factor of ten smaller than before. Only one point per line needs to be explored to determine the nucleosynthesis for a particular value of $\dot{M}$. The horizontal line through the middle of the plot simply emphasizes that each unique value of $\dot{M}$ can be reached using a single value of $d$ (namely $10^{12}$ cm), if $\dot{M}_\odot$ is allowed to vary between $10^{-4}$ and $10^4$.

The three example cases presented in the next three sections correspond to clumps with $d = 10^{13}$, $10^{11}$, and $10^{12}$ cm, which we refer to as large, small, and medium, respectively. For each of these three values of $d$, there are three possible values of $\dot{M}_\odot$, shown as the circles in Figure 4.1. Note that each line representing a separate value of $\dot{M}$ passes through exactly one of the circles. We therefore obtain uniform coverage of the parameter space for $\dot{M}$.

Several trends reduce the complexity of the parameter search. Many of the abundance production results depend steeply on the temperature. This reduces the effective parameter space by eliminating the need to carefully examine temperatures
which are far from the value at which optimal production occurs. Furthermore, except in cases where the density is kept constant, the initial density has only a small effect on the final abundance concentrations. Therefore, values of the initial density which are far below the final density do not need to be explored.

4.2 Large Clump Sizes

An example of the abundance evolution for clumps with $d = l = 10^{13}$ cm is given in Figure 4.2. We will call this Case A.

4.2.1 General Features

Since plots similar to this one appear throughout the chapter, we first pause to explain general features common to all such plots. The x-axis represents time in years, and the y-axis is number abundance in particles per cm$^3$. It is important to note that both axes are shown with a logarithmic scale. Since the metals C, N, and O (collectively referred to as CNO) begin with zero abundance$^1$, the y-axis spans a very broad range in abundance so that the early evolution of these and other metals can be seen on the plot.

$^1$Recall that for simplicity, we assume zero primordial concentrations for all elements heavier than $^7$Li. Estimates from homogenous big bang nucleosynthesis for primordial abundances of CNO are $10^{-15}$, $10^{-16}$, and $10^{-19}$, respectively.
Figure 4.2: Abundance evolution for Case A. Final number abundance ratios with respect to hydrogen are given for selected nuclei below the plot. The high final metal concentrations for this figure should not be taken seriously, because the processing time is long, and the final clump mass is unrealistically large.
Values of all the variable parameters for a particular run are listed above the corresponding abundance plot. Table 4.1 gives the full names of the parameters whose symbols appear in this list.

Time evolution of the abundance for each illustrated nuclide proceeds from left to right. The curves for nuclei with nonzero initial abundances can be seen entering the plot horizontally on the left hand side. Topmost of these is \(^1\text{H}\). Just below this is \(^4\text{He}\). \(^2\text{H}\) and \(^3\text{He}\) are next, and these two overlap since we use identical initial abundances for these elements. Because it is not a key player in the nucleosynthesis and its abundance curve would just add extra clutter to the plot, \(^7\text{Li}\) is not shown, but it would appear initially below the \(^2\text{H}\) and \(^3\text{He}\) at \(10^8\) particles/cm\(^3\) (i.e., roughly \(10^{-10}\) below \(^1\text{H}\)).

Although the calculation is performed using the mole fractions \(Y_i\) for each nuclide \(i\), the results are displayed using the number abundances \(n_i\). In this way, a more direct comparison can be made with the abundance ratios estimated from the ionization models discussed in Chapter 2. Recall that mole fractions and number abundances for species \(i\) are related by the equation \(n_i = Y_i \rho N_A\), where \(\rho\) is the mass density in g/cm\(^3\).

Listed below each plot are several final number abundance ratios with respect to the final hydrogen number abundance. Comparing these ratios with the solar ratios for the same elements allows one to assess the metal production. In Figure 4.2, the final abundance ratios are extremely high compared to standard solar values, which
are given in Table 2.1. We discuss this further in the section dealing with the specific features of Case A.

The high mass end point of our reaction network is $^{24}\text{Mg}$. All material which would flow to higher masses (if we had included more reactions on heavier nuclei) accumulates as $^{24}\text{Mg}$. Therefore, we do not show the the curve for this nuclide on the abundance plots, because the number of $^{24}\text{Mg}$ nuclei in the simulation can be artificially enhanced by the end point accumulation. Final ratios of $^{24}\text{Mg}$ to $^1\text{H}$ are provided in the text as an indicator of the total metal production possible for a given set of parameters.

For Case A, the final $^{24}\text{Mg}$ abundance is $2.24 \times 10^6$ times higher than the proton abundance. This means that $^{24}\text{Mg}$ is the most abundant element after $^4\text{He}$. Much of the material labeled $^{24}\text{Mg}$ may in fact end up as higher mass material if we had included more thermonuclear reactions on heavier nuclei, and so our network is fairly incomplete for these densities and time scales. Not all of the other parameter combinations shown below exhibit this extreme buildup of $^{24}\text{Mg}$.

The effect of mass deposition by the jet can be seen in the proton and alpha particle number abundances. When the amount of mass introduced by the jet approaches the mass initially present in the clump, the $^1\text{H}$ and $^4\text{He}$ abundances begin to increase linearly with time. This happens at about $10^{-2}$ years in Figure 4.2. At later times in Figures 4.2, the proton abundance drops while the $^4\text{He}$ abundance keeps increasing. These kinks and turns will be explained later, as they are specific to the particular...
set of parameters used in generating the figure. The initial rise in slope of the $^1\text{H}$ and $^4\text{He}$ abundances will occur in almost every plot we show.

As will be the case in many subsequently presented results, $^7\text{Be}$ plays a key role in the production of higher masses. Especially at early times in Figure 4.2, the reaction processes which create $^7\text{Be}$ and $^{11}\text{C}$ are characteristic of the nucleosynthesis in many other parameter combinations besides Case A. The first important reaction is $^4\text{He}(\alpha,\text{n})^7\text{Be}$, a level 1 jet-clump reaction which causes the initial rise in the amount of $^7\text{Be}$. The $^7\text{Be}$ abundance levels off when destruction via the thermal reaction $^7\text{Be}(\text{n, p})^7\text{Li}$ balances the input from the beam reaction. When both $^3\text{He}$ and $^4\text{He}$ begin to rise, $^7\text{Be}$ production increases dramatically through the thermonuclear reaction $^3\text{He}(\alpha,\gamma)^7\text{Be}$. Recall that for such a reaction, the rate depends on the number abundance of both species in the entrance channel, and so if these abundances are increasing, the rate for $^7\text{Be}$ production will increase according to their product. Since the rate of $^7\text{Be}$ production is increasing, the amount amount of $^7\text{Be}$ produced rises very rapidly. $^{11}\text{C}$ (not shown in Figure 4.2) experiences a similar boost in production through $^7\text{Be}(\alpha,\gamma)^{11}\text{C}$ due to the simultaneous increase of the $^7\text{Be}$ and alpha particle abundances. Nearly all of the $^{11}\text{C}$ produced is then converted to $^{11}\text{B}$ through $\beta$ decay. $^{11}\text{B}$ undergoes $^{11}\text{B}(p,\gamma)^{12}\text{C}$, and CNO cycle reactions on $^{12}\text{C}$ produce $\text{N}$ and $\text{O}$, and subsequently $\text{Ne}$ and $\text{Mg}$.

This pattern of production through $^7\text{Be}$ and $^{11}\text{C}$ is the primary mechanism of significant metal generation in our model. Recall that $^7\text{Be}$ has a very long lifetime against electron capture given the high temperature conditions of our model. Since
it has a mass between the stability gaps at $A=5$ and $A=8$. $^7$Be is uniquely positioned to serve as a bridge to higher masses.

### 4.2.2 Specific Features

The metal abundances at late times in Figure 4.2 are dramatically high. The protons are consumed by $(p,\gamma)$ reactions in the CNO cycle, and a large drop in the proton abundance occurs after about $10^2$ years. By $10^4$ years, the concentrations of C, O, Ne, and Mg are approaching that of the protons. Not shown in the figure is the neutron abundance, which rises significantly at later times and destroys much of the $^7$Be through $^7$Be(n,p)$^7$Li. The production of higher masses does not slow down at this point, however, because the density is now high enough that the triple alpha process\(^2\) can make $^{12}$C. At such high densities, the heaviest elements in our simulation are copiously produced. As mentioned earlier, $^{24}$Mg (the endpoint of our reaction network) becomes more abundant than the protons. This indicates that if we had included reactions on $^{24}$Mg leading to higher mass elements, these reactions could result in the generation of a significant amount of elements heavier than $^{24}$Mg.

\(^2\)The triple alpha process is just the reaction $^4$He$(2\alpha,\gamma)^{12}$C. Since there are three particles in the entrance channel, this reaction depends on one higher power of the density than 2 body reactions. Thus it makes a significant amount of $^{12}$C only at relatively high densities.
Figure 4.3: Clump velocity resulting from the parameter combinations given for Case A. Assuming that the clump is isolated and that no mechanism exists by which the clump can lose momentum, the absorption of high velocity jet material will cause the velocity of the clump to eventually approach the velocity of the jet.

4.2.3 Cautionary Note about the Parameters

Although the metal production is indeed remarkable for the clump characteristics used in creating Figure 4.2, other implications for this parameter combination need to be considered. In fact, the concerns we raise here will affect nearly all of our results. Although the confinement mechanisms for quasar gas are not well understood, the final density of $2 \times 10^{23}$ particles/cm$^3$ in Figure 4.2 is certainly extreme. Furthermore, the final clump mass is very large, since it has been absorbing $10 ~ M_\odot$ per year for $10^5$ years. The total mass of the BLR is estimated to be on the order of $10 ~ M_\odot$, and so it is unlikely that the clump mass could become so large.

Yet another consideration for this scenario is the momentum absorbed by the clump. The accumulation of clump mass comes from the stopping of high velocity jet material, and if no process exists to slow down the clump, then its velocity will soon approach that of the jet. Figure 4.3 shows $v/c$ for the parameter values used in
Case A (Figure 4.2). When the clump density has increased tenfold (after about 1 year), the bulk velocity of the clump gas is over half the average jet velocity. After 10 years, the clump is essentially moving at the same speed as the jet. Thus the clump is quickly swept up by the jet. If the clump leaves the central region of the quasar, then it can no longer avail itself of the heating mechanisms which exists there, and the thermal nucleosynthesis will die down at the resulting lower temperatures.

Finally, since we use a single zone model, we must assume that all stopped material is distributed throughout the clump volume. But if the clump is large and the density is high, the jet material can be stopped in a thin layer at the incident face of the clump. Our one zone model gives accurate results only if a mechanism is present to mix all of the recently stopped material throughout the rest of the clump. According to Figure 3.4, the thickness needed to stop 1000 A MeV projectiles (with charge $Z=1$) is about $10^{26}$ electrons/cm$^2$. When the cylindrical clump is $10^{14}$ cm long and has a density of $10^{18}$ particles/cm$^3$, the total thickness is $10^{32}$ electrons/cm$^2$, and so the jet is stopped in a very small fraction of the clump. The overdense region containing the newly stopped jet particles is likely to expand into other portions of the clump, providing a degree of mixing. For large clumps, however, this expansion may not be able to provide adequate mixing.

Figure 4.2 thus illustrates the dramatic levels of metal production which can occur in the jet–clump model if the parameters are set so that the clump is allowed to have a long processing time. We do not explore clumps with $d = l = 10^{14}$ cm simply
because they require even longer times to build up significant metal concentrations, thus exaggerating the problems mentioned above.

Since \( d \) is equal to \( 10^{13} \) cm, Case A corresponds to the far right point in the topmost row of three points in Figure 4.1. The other two points are not presented here, because they involve lower values of \( \dot{M}_\odot \). Less mass input per time (i.e., lower \( \dot{M}_\odot \)) corresponds to a slower density increase and longer processing times. As mentioned above, the long time required for the abundance evolution in Case A present significant difficulties which are only made worse if the time is extended further.

The density is allowed to grow unrestrained in Case A. If the density evolution is changed so that the clump density can only climb to a certain level, then a slightly different evolution pattern which takes less time will result. Similar results as obtained in Section 4.4 can be observed for the parameters used in Case A if \( \rho_{N1} \), the final maximum number density, is changed to \( 10^{21} \) particles/cm\(^3\). The time required to reach the maximum density is of course still longer than for the results in Section 4.4, which deals with clumps having a size \( d = 10^{12} \) cm.

4.3 Small Clump Sizes

Many of the problems presented in the previous section can be eliminated by using a smaller clump size so that the density builds up faster and the overall time for the evolution is reduced. For some combinations shown below, the abundance evolution is complete within just a few days. The fact that the clump is swept up by the jet now becomes less of an issue, because the nucleosynthesis may still be able to occur.
within the short time scale. Mixing may also be more vigorous in these cases. The short evolution means that much less total mass is deposited in the clump, which is more in line with the known mass of gas on the outskirts of quasar cores.

For the abundance evolution presented in this section, we restrict the density growth to a limiting maximum value. Instead of $\rho_N = \infty$ as in the last section, we test the metal production for $\rho_N = 10^{20}$ particles/cm$^3$ through $10^{22}$ particles/cm$^3$.

We present Case B in Figure 4.4. The clump size is $d = l = 10^{11}$ cm, the small value in the range we explore. Values of all parameters for the Case B are listed at the top of the figure. The smaller volume of the clump causes the density to increase much more rapidly than in Case A. Note that the time scale on the x-axis for Case B is days rather than years.

The density in Case B is only allowed to climb up to $10^{21}$ particles/cm$^3$. Once the maximum density is reached, an equal amount of material as flows in from the jet also flows out of the clump. All outflowing material is assumed to have the same composition as the gas remaining in the clump. When the density levels off at the maximum value, the nucleosynthesis soon reaches an equilibrium state. No further enhancements to the metal concentrations in the clump are achieved, because the supply of building blocks from the jet is no longer increasing. However, metals are still being created. The jet material flowing in is primordial, but the material flowing out has the same abundances as the equilibrium concentrations in the clump.

A key feature of the evolution shown in Figure 4.4 is the short amount of time needed to reach the equilibrium state. Only 3 days are needed for the density to
Figure 4.4: Case B showing the evolution for a clump size of $10^{11}$ cm. Within the ranges specified in Table 4.1, the parameter values listed above give the optimal production for a clump size of $10^{11}$ cm. Final abundance ratios for CNO are about 4 to 5 orders of magnitude below solar levels.
attain the maximum level. The abundance curves for most nuclei flatten out at the same time, although some of the higher mass metals require a few more days to reach their equilibrium abundances.

The rapid rise of the CNO abundances again centers around the $^7\text{Be}$ abundance, which is initially sustained by the jet–clump reaction $^4\text{He}(\alpha, n)^7\text{Be}$ and later generated by the thermal reaction $^3\text{He}(\alpha, \gamma)^7\text{Be}$. Because both the $^7\text{Be}$ abundance and the $^4\text{He}$ abundance are increasing, $^{11}\text{C}$ production through $^7\text{Be}(\alpha, \gamma)^{11}\text{C}$ increases very rapidly. Further discussion about the pathways for the nucleosynthesis and the resulting abundance ratios are given in section 4.3.3, which describes how the abundance production for case B varies with clump temperature. Final number abundance ratios of $^{12}\text{C}$, $^{14}\text{N}$, and $^{16}\text{O}$ are between $10^{-4}$ and $10^{-5}$ of their solar values.

The final abundance of $^{24}\text{Mg}$ in Case B is $1.76 \times 10^{-11}$. Recall that this is not a true abundance, but, because we only include reactions up to this nuclide, all flow which might occur to heavier elements is accumulated as $^{24}\text{Mg}$.

### 4.3.1 Altering the Mass Input Rate

The jet mass rate in Case B is $\dot{M}_\text{J} = 0.1$ (i.e. 0.1 solar masses per year), which is on the low end of the values we examine. For jet mass input rates higher than this, the equilibrium state is reached sooner, which means that the CNO abundances will flatten out at levels lower than those of Figure 4.4. Two cases with higher jet mass input rates are shown in Figures 4.5 and 4.6, which show the results for $\dot{M}_\text{J}$ of 1.0 and 10.0, respectively.
Figure 4.5: Abundance evolution similar to that in Case B (Figure 4.4), but with a larger $M_\odot$ of 1.0. The equilibrium abundances are reached at earlier times when the CNO nuclei are at lower levels than in Case B.
Figure 4.6: Abundance evolution similar to that in Case B (Figure 4.4), but with a larger $M_\odot$ of 10.0.
The restraining factor in each of Figures 4.4, 4.5, and 4.6 is the time. In Section 4.4, we explore parameter combinations using a larger clump. The extra time gained by having a larger volume to fill can make a significant difference in the metal production, since the slope of the metal abundance lines are so steep.

For completeness, the final accumulation within the $^{24}\text{Mg}$ abundance in Figure 4.5 is $5.49 \times 10^{-16}$ and for Figure 4.6 it is $1.22 \times 10^{-20}$. As before, these numbers are ratios of the final $^{24}\text{Mg}$ number abundance (representing production of mass 24 and higher) with respect to the final $^{1}\text{H}$ abundance.

### 4.3.2 Altering the Jet Energy

The mean energy of the jet particles in each of Figures 4.4 through 4.6 is 100 A MeV. If the jet energy is increased, a larger fraction of $^4\text{He}$ nuclei in the jet are destroyed by jet-clump reactions before they are degraded in energy to the point where the $^4\text{He}(\alpha,n)^7\text{Be}$ reaction cross section is large. As shown in Figure 3.10 of Chapter 3, less than 1% of all the $^4\text{He}$ initially incident at 1000 A MeV will survive to be degraded below 100 MeV (note that this is MeV and not MeV/amu). Thus higher jet energies result in a smaller yield for $^7\text{Be}$ through the $^4\text{He}(\alpha,\gamma)^7\text{Be}$ jet-clump reaction. Less $^7\text{Be}$ means slower creation of $^{11}\text{C}$ through $^7\text{Be}(\alpha,\gamma)^{11}\text{C}$, and thus less CNO production. The final abundances of $^{12}\text{C}$, $^{14}\text{N}$, $^{16}\text{O}$, and $^{20}\text{Ne}$ relative to $^{1}\text{H}$ are shown as a function of the mean jet energy in Figure 4.7. No other parameters are changed except the jet energy. The final abundance refers to the equilibrium values after the density reaches its maximum of $10^{21}$. The drop in all these abundances
Figure 4.7: Final metal abundances versus incident jet energy with all other parameters fixed to the values used in Case B. Each vertically aligned set of points represents a set of final abundances for a given jet energy. The lines do not represent additional data, but merely help guide the eye.
with increasing jet energy is due to the decreasing supply of $^7\text{Be}$ from the jet-clump reaction.

### 4.3.3 Altering the Temperature

The effect of varying the temperature on the abundance evolution is presented in Figure 4.8. There are several competing issues regarding the temperature which together determine the net metal production. Nearly all metal production flows through the reaction $^7\text{Be}(\alpha,\gamma)^{11}\text{C}$. So in order to maximize CNO abundances, the $^7\text{Be}$ abundance must also be maximized. At late times, $^7\text{Be}$ is produced mainly by the thermonuclear reaction $^3\text{He}(\alpha,\gamma)^7\text{Be}$ (number 38 in table 3.3). Jet-clump reactions provide a steadily increasing number abundance of $^3\text{He}$ which sustains $^7\text{Be}$ production. As the temperature is decreased, the rate for reaction 38 is less, and not as much $^7\text{Be}$ can be produced. If the temperature is increased, then the rate for reaction 38 will increase, but so will other rates for reactions which destroy $^7\text{Be}$. The rate for photodestruction of $^7\text{Be}$ (i.e., the $\gamma$ induced inverse of reaction 38) increases more rapidly with temperature than the corresponding forward rate, so eventually a temperature is reached where $^3\text{He}(\alpha,\gamma)^7\text{Be}$ (coupled with its inverse) can be a net destroyer of $^7\text{Be}$. Other destruction reactions on $^7\text{Be}$ include $^7\text{Be}(n,p)^7\text{Li}$ (reaction 28) and $^7\text{Be}(p,\gamma)^8\text{B}$ (reaction 51). The neutrons for fueling reaction 28 are liberated from the $^2\text{H}$ produced in several jet-clump reactions. The inverse rate for reaction 28 is very small because most protons incident on $^7\text{Li}$ initiate the reaction $^7\text{Li}(p,\alpha)^4\text{He}$. Reaction 51 is interesting because the rate for its inverse is very high. The $Q$ value for
the reaction is only 0.137 MeV, and so the $^8$B is easily destroyed in an environment with $T_9 \sim 1$. In all parameter combinations presented in this chapter, the forward and reverse rates of reaction 51 are nearly equal, and no net flow of $^7$Be to $^8$B occurs. If the photodestruction rate of $^8$B were not so high, the $^7$Be abundance would be very low, since $^8$B readily $\beta$ decays (with a half life less than one second) to $^8$Be, which lasts only $10^{-16}$ seconds before breaking up into two alpha particles.

The metal production as a function of temperature can also be understood through the $^{11}$C abundance. Once $^{11}$C is reached, there are no significant pathways back down to lower masses. In other words, all destruction of $^{11}$C leads to other nuclei with masses above 10. Unlike the case with $^7$Be, production of higher masses from $^{11}$C only increases for higher temperatures, because there are no competing destruction reactions. So although the optimal creation of $^{11}$C requires an intermediate temperature due to the dependence on the reaction $^7$Be($\alpha$,\gamma)$^{11}$C, the generation of higher masses past $^{11}$C benefits from as high a temperature as possible.

Since the destruction and creation rates for any given nuclei depend not only on the temperature but also on abundances of other nuclei, it is difficult to predict the optimal temperature apart from a full nucleosynthesis calculation. Final CNO, $^{20}$Ne, $^7$Be, and $^{11}$C abundances resulting from calculations at various temperatures are plotted in Figure 4.8. All other parameters are kept the same as those in Case B (Figure 4.4). The $^7$Be abundance and $^{11}$C abundance are both sharply peaked at the optimal temperature of $T_9 = 0.6$ due to the competition between creation and destruction of $^7$Be. Final abundances for CNO and the other nuclei show less
Figure 4.8: Final metal abundances versus clump temperature with all other parameters set to the values used in Case B. Each vertically aligned set of points represents a different temperature. The lines are only a guide to the eye and the abundances are displayed in different panels to prevent data points from overlapping.

rapid decreases as the temperature is increased above the optimal value, because although there is less $^{12}$C at the higher temperature, the faster rates allow more rapid conversion of the $^{12}$C to higher mass nuclides.

Calculations were performed at temperatures up to $T_g = 5.0$, and the resulting abundances follow the trends shown in Figure 4.8. Since the final metal abundances in these cases are very low, we merely mention here that for all parameter combinations explored, temperatures above $T_g = 2.0$ are not capable of significantly contributing to quasar metal production.
4.3.4 Altering the Final Density

The last parameter to examine is the final density. Abundance evolution for final densities of $10^{20}$ particles/cm$^3$ and $10^{22}$ particles/cm$^3$ are shown in Figures 4.9 and 4.10 respectively. All other parameter values are those of Case B. The main effect of altering the maximum density is in the time required to reach equilibrium. In Figure 4.9, the clump density reaches the maximum in just 0.5 days, at which point the CNO abundances are still very low. The final value of the $^{24}$Mg to $^1$H ratio is also very low, at $1.87 \times 10^{-20}$. Decreasing the maximum density below $10^{20}$ particles/cm$^3$ further reduces the metal production.

Figure 4.10 shows the evolution if the final density can climb 10 times higher than in Case B. The final abundances in the higher density scenario show substantially more processing at late times. We delay an explanation of why this processing takes place until the next section (4.4). If such advanced processing can occur, then the final metal abundance ratios can begin to approach solar values. The final value of the $^{24}$Mg to $^1$H abundance, $1.99 \times 10^9$, is slightly higher than the same ratio for $^{16}$O. Since $^{24}$Mg is the high mass end point of the network, a significant amount of metals heavier than those we have simulated may also be produced.

The evolution in the higher density case of Figure 4.10 takes about 100 days to reach equilibrium concentrations. Increasing the jet mass input rate can speed up the evolution. If $\dot{M}_\odot$ is raised to 1.0, and all other parameters are the same as in Figure 4.10, then a similar abundance evolution pattern as occurs for $\dot{M}_\odot = 0.1$ can occur on
Figure 4.9: Abundance evolution similar to that in Case B (Figure 4.4), but with a lower final density, \( \rho_{nf} = 10^{20} \) particles/cm\(^3\).
Figure 4.10: Abundance evolution similar to that in Case B (Figure 4.4), but with a higher final density, \( \rho_{N_f} = 10^{22} \) particles/cm\(^3\). The drop in the proton abundance and other features resulting from this drop are discussed in Section 4.4.
a time scale of about 10 days. However, if $\dot{M}_\odot$ is increased further to 10.0, then the maximum density ($10^{22}$ particles/cm$^3$ in both Figure 4.9 and 4.10) is reached before the CNO nuclides can climb to the critical level where they begin to consume the protons. Final abundances when $\dot{M}_\odot = 10.0$ and $\rho_{N\ell} = 10^{22}$ particles/cm$^3$ are fairly low and are similar to those of Case B.

4.3.5 Discussion

The jet provides the critical feature which allows the steep increases in CNO abundances. Number densities for many particle species are increasing due to deposition from the jet or from jet-clump reactions. Production rates for some nuclei increase according to the product of two such increasing number densities. $^7\text{Be}$, for example, is created by $^3\text{He}(\alpha,\gamma)^7\text{Be}$. Since $^3\text{He}$ and $^4\text{He}$ are both increasing proportionally with the density, the abundance of $^7\text{Be}$ can rise as the density squared. $^{11}\text{C}$ is produced by $^7\text{Be}(\alpha,\gamma)^{11}\text{C}$. Since $^7\text{Be}$ increases as density squared and $^4\text{He}$ as density to the first, the $^{11}\text{C}$ abundance can rise with the density to the third power. Thus the fact that the density increases is crucial in our model.

Abundance evolution scenarios shown in this section are for clumps with $L = d = 10^{11}$ cm, which represents the lowest row of points in the plot of $d$ vs. $\dot{M}_\odot$. Each of the three possible values of $\dot{M}_\odot$ are examined. Also, the density is only allowed to reach a maximum level of $10^{20}$, $10^{21}$, or $10^{22}$ particles/cm$^3$. In most situations, the
final abundances, although far above primordial levels\(^3\), still fall short of the solar ratios observed in quasar spectra. If the temperature is near \(T_9 = 0.6\) and the final density can reach \(10^{21}\) particles/cm\(^3\), then Figure 4.4 indicates that the abundances may be able to climb to within \(10^{-4}\) of the solar values in just a few days. However, if the temperature is much higher or lower, significantly less CNO production will occur. Final metal abundances also decrease for higher jet energies, larger jet mass input rates, and lower final densities.

If the density can reach \(10^{22}\) particles/cm\(^3\), then metal generation approaching solar levels can occur for clumps with \(d = 10^{11}\) cm. For this final density, the time needed to achieve the high concentrations depends on the mass input rate. For \(\dot{M}_\odot = 0.1\), the time scale is 100 days, and for \(\dot{M}_\odot = 1.0\) it is 10 days. With \(\dot{M}_\odot = 10.0\), the production is the same as in the lower density case.

At this point, the abundance evolution for \(\dot{M}\) with values taken from the top and bottom rows of points in Figure 4.1 has been discussed. The top row with \(d = 10^{13}\) cm gives processing times which are longer than realistically possible. In contrast, smaller clumps with \(d = 10^{11}\) cm allow more realistic processing times. but in these clumps the metal abundances are driven to equilibrium values before they can trigger the proton consumption. Next we examine medium sized clumps which also allow for intermediate processing times.

\(^3\)Recall that primordial number abundance ratios to \(^1\)H for CNO from Kajino, Matthews, & Fuller (1990) are \(10^{-15}\), \(10^{-16}\), and \(10^{-19}\), respectively.
4.4 Medium Sized Clumps

Clump sizes of \( d = l = 10^{12} \) cm are considered in this section. The example plot for this section is Case C, shown in Figure 4.11. Since \( M_\odot = 1.0 \) and \( d = 10^{12} \) cm, Case C corresponds to the middle point of the parameter space in Figure 4.1.

4.4.1 Proton Depletion

The crucial feature in this abundance evolution is the drop in the proton abundance. A similar drop occurs in Figure 4.10, the last abundance plot of the previous section (4.3). A more dramatic version of the same effect also can be seen in Case A (Figure 4.2), the very first abundance plot of the chapter. The crucial event in each of these scenarios occurs when the CNO nuclides reach a level where rates for \((p, \gamma)\) reactions on the metals actually begin to affect the concentration of hydrogen in the clump.

As the protons are being depleted, the \(^4\)He abundance shows a slight increase. When there is a high proton concentration in the clump, a significant fraction of the \(^4\)He in the jet is destroyed by jet-clump reactions on the ambient protons. As the protons decrease in number abundance, a larger fraction of the incident \(^4\)He can survive to be deposited in the clump.

Because \(^4\)He becomes more concentrated in the clump, the target fraction (the ratio of the target nuclide number density to the electron number density) for \(^4\)He increases, and the yield goes up for all jet-clump reactions using \(^4\)He as a target. In particular, \(^7\)Be shows a sharp increase at this time through increased production
Figure 4.11: Case C showing abundance evolution for clumps with a size of $10^{12}$ cm. The metals reach a level sufficient to initiate substantial consumption of the protons. When this occurs, the final ratios of the metals can approach solar levels.
in the jet-clump reaction \(^4\text{He}(\alpha,\text{n})^7\text{Be}\). Many other thermonuclear reaction rates depend on the abundance of hydrogen. If a key destruction reaction for a nuclide involves a proton in the entrance channel, then when the proton abundance drops, the net production rate of such a nuclide will increase.

The final concentrations for CNO nuclides in Figure 4.11 are relatively close to solar levels. \(^{12}\text{C}\) and \(^{14}\text{N}\) are about two orders of magnitude below the solar values, but \(^{16}\text{O}\) is about 250 times its solar level, and \(^{20}\text{Ne}\) is over 6 times solar. \(^{24}\text{Mg}\) is slightly more abundant than \(^{16}\text{O}\). Since \(^{24}\text{Mg}\) is the highest mass in the network, its abundance should be regarded as the sum of all material with a mass of 24 or greater.

Much of the enhancement resulting in ratios near or above solar levels is due to the fact that the proton concentration is reduced significantly below its primordial value. Subsequent mixing of primordial material with gas processed by jet-clump interactions will reduce the abundance ratios below the values quoted below each figure.

4.4.2 Altering the Mass Input Rate

With \(l = d = 10^{12}\) cm. substantial levels of abundance production occur for all values of \(\dot{M}_\odot\) in the range 0.1 to 10.0. Figures 4.12 and 4.13 show the resulting evolution patterns for \(\dot{M}_\odot\) of 0.1 and 10.0, respectively. All other parameters in these plots take on the values given in Case C. In the plot with lower \(\dot{M}_\odot\), the abundances reach higher levels because it takes more time to reach the maximum density, and the metal
concentrations can climb to a higher level before they are forced to equilibrium values by the outflow from the clump.

In the two scenarios shown in Figures 4.12 and 4.13 (as well as in Case C, see above), the pileup of material in the endpoint of the reaction network is significant. The value quantifying this pileup is the ratio of the final $^{24}\text{Mg}$ abundance to the final $^{1}\text{H}$ abundance. In Figure 4.12, $^{24}\text{Mg}$ is the most abundant element after $^{4}\text{He}$, with a final ratio to $^{1}\text{H}$ of $4.02 \times 10^0$. In Figure 4.13, this ratio is much less, $6.85 \times 10^{-4}$, but $^{24}\text{Mg}$ is still the fourth most abundant element of those shown.

4.4.3 Altering the Jet Energy

For the same reasons given in Section 4.3.2, higher jet energies result in lower final metal production. The higher the jet energy, the less $^{4}\text{He}$ can survive destruction by jet-clump reactions to the low energies where the cross section of the $^{4}\text{He}(\alpha,n)^7\text{Be}$ jet-clump reaction is large. Production as a function of jet energy for selected nuclei is given in Figure 4.14.

4.4.4 Altering the Temperature

As expected, the abundance production for clumps with $d = 10^{12}$ cm is a sensitive function of the temperature. Figure 4.15 shows how the metal production drops very sharply for temperatures away from the optimal value. The sensitivity here is more pronounced than in Section 4.3. If the temperature only allows limited amount of
Figure 4.12: Abundance evolution similar to that in Case C (Figure 4.11), but with lower $M_\odot$ of 0.1.
Figure 4.13: Abundance evolution similar to that in Case C (Figure 4.11), but with higher $M_\odot$ of 10.
Figure 4.14: Final metal abundances versus incident jet energy for clumps with a size of $10^{12}$ cm. Each vertically aligned set of points represents a separate run of the simulation. Only the jet energy was varied and all other parameters are the same as those used in Case C (Figure 4.11). The lines are merely a guide to the eye.
Figure 4.15: Final metal abundances versus clump temperature. Each vertically aligned set of points represents a different temperature. All other parameters are kept the same and have the values used in generating Case C. The lines are only a guide to the eye. The abundances are displayed in different panels to prevent the data points from overlapping each other.

early metal production, then the metals cannot climb to the critical level where the protons can be depleted, and the final abundance ratios are much lower.

4.4.5 Altering the Final Density

The CNO production in our model has two distinct modes. The high production mode results from the proton depletion, and the low production mode occurs otherwise. The final density is a key parameter in allowing the proton depletion to occur. Keeping all other parameters the same as in Case C and lowering the final density from $10^{21}$ to $10^{20}$ particles/cm$^3$ is enough to move from the high to the low production scenario. Figure 4.16 shows the evolution for this case. The final ratio of material
Figure 4.16: Abundance evolution similar to that in Case C (Figure 4.11), but with a lower final density of $10^{20}$ particles/cm³. In this case, the protons continue to increase and the final metal concentrations remain low.
accumulating at $^{24}\text{Mg}$ to the final $^1\text{H}$ abundance is $5.64 \times 10^{-12}$, which would appear slightly above the $^{20}\text{Ne}$ abundance in Figure 4.16.

If the final density is increased above $10^{21}$ particles/cm$^3$ (no figure is shown for this, because the production is very similar qualitatively to that in Case C), then the metal production will also increase. For higher final densities, not only can the critical metal levels be reached in order to trigger the proton turnover, but the changing of protons into other nuclei decreases the number density in the clump. The evolution can then continue for a while longer until the total number density (of heavier particles) reaches its maximum value.

### 4.4.6 Discussion

If the maximum density is set to $10^{21}$ particles/cm$^3$, clumps with $l = d = 10^{12}$ cm offer the largest region of parameter space for producing near solar ratios of CNO. If the final density can reach $10^{21}$ particles/cm$^3$ and the temperature is near $T_9 = 0.6$, then the abundance evolution for the entire allowed range of $\dot{M}_\odot$ results in final CNO to $^1\text{H}$ ratios not too far below solar values. The shortest processing time of 100 days occurs if $\dot{M}_\odot = 10.0$. If the density can climb higher than $10^{21}$ particles/cm$^3$, then final metal production can be higher, but if the maximum density reachable is only $10^{20}$ particles/cm$^3$, then the proton depletion will not occur and final metal abundance ratios are much lower.
4.5 Constant Density Evolution

If the density in the clump does not increase due to jet mass deposition, then the resulting nucleosynthesis will be very limited. For completeness, we do show an example of the abundance evolution for such a scenario in Figure 4.17. The final metal abundances do rise somewhat above primordial levels, but are still a factor of $10^{-10}$ below corresponding solar values. Buildup of material at the high mass end of the network is not significant for this constant density case. The final abundance ratio of $^{24}\text{Mg}$ (which represents the abundance of material of mass 24 or higher) to $^1\text{H}$ is of order $10^{-24}$.

4.6 Thin Clumps

Finally, we provide a brief discussion of the scenario in which the clump thickness is not sufficient to stop the jet.

Figure 4.18 shows the abundances versus time for a clump with a length of $10^{13}$ cm and an initial particle density of $10^{11}$ particles/cm$^3$. Initially, all jet particles pass completely through the clump without being stopped. A fraction of the jet particles will, however, participate in jet-clump reactions. At first, the $^4\text{He}$ abundance begins to drop as jet-clump reactions utilizing $\alpha$ particle targets begin to deplete the supply of $^4\text{He}$. $^1\text{H}$ is not depleted because, although some jet-clump reactions destroy protons, other similar reactions are net producers of $^1\text{H}$. $^4\text{He}$ is not created in any jet-clump reactions. Therefore the clump begins to run out of $^4\text{He}$. 

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Figure 4.17: Abundance evolution for a constant density of $10^{18}$ particles/cm$^3$. The maximum final CNO abundances for any constant density scenario explored are about 10 orders of magnitude below solar levels.
Figure 4.18: Abundance evolution in the case where the clump is not thick enough to stop the jet. With an initial column density of $10^{25}$ particles/cm$^2$, the clump depicted here initially allows all the jet particles to pass through without being stopped. Eventually, the deposition of jet-clump reaction products raises the column density to a level capable of stopping the jet. At this point the density increases very sharply. The final $^{12}$C abundance is between that of $^7$Be and $^{14}$N. Note that the axes on this plot are different than for other abundance plots in this chapter.
The clump thickness is sufficient to stop much of the $^3$He and $^3$H produced in jet-clump reactions. The particle density of the clump increases due to this deposition, and eventually the density becomes high enough to stop the primary jet particles. At this point, the $^4$He and $^1$H abundances shoot up, and all jet-clump reactions which depend on the $\alpha$ particle abundance also show sharp increases. The final density in this case is a maximum of $10^{14}$ particles/cm$^3$, a level which is soon reached after the clump begins to stop the jet. Although the sudden increases are dramatic, the final metal abundances are are still very low.

The final CNO abundances in Figure 4.18 are in fact somewhat lower than primordial values. The abundance of $^{24}$Mg, the high mass endpoint of the network, has a value below that of $^{20}$Ne. The production is limited in this case because the final density is not allowed to reach the levels in previous scenarios. In order for the jet to be able to penetrate the clump, the initial clump density must be small. The final density for this clump is $10^3$ times greater than the initial density. If this disparity can be larger so that the final density climbs much higher, then production at later times is closer to that for other higher density cases. Recall that higher final densities will take a longer time to reach equilibrium values.

The temperature in Figure 4.18 is $T_9 = 1.4$, which is higher than the optimal temperature in Case B or Case C. For the low density evolution shown in the figure, this temperature gives the highest metal production for fixed values of all other parameters. If the density can increase to higher levels, then the optimal temperature is closer to the value of $T_9 = 0.6$. 

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In order for the jet to pass through a clump with an initial column density of $10^{25}$ particle/cm$^3$, the average jet particle energy must be above about 140 A MeV. Otherwise, some of the jet particles will not be energetic enough to make it all the way through the clump. If the jet energy is higher than 300 A MeV (the energy used in Figure 4.18), less initial deposition occurs, and the $^4$He abundance drops more than in Figure 4.18.

One interesting consequence of the thin clump scenario is the large final abundance of $^3$He, which is even higher than that of $^4$He. The production of significant amounts of $^3$He by collisions between jet nuclei and clump nuclei has interesting possibilities for the chemical evolution of $^3$He, which we discuss further in the next chapter.

4.7 Summary

Metal production in the jet-clump model has been presented for a variety of conditions. For a few cases, the final metal abundances can approach solar levels, but the majority of conditions explored are not conducive to significant CNO production.

The final abundances in all cases depend sensitively on the temperature. All paths to higher masses go through $^7$Be and $^{11}$C, and so the concentrations of these nuclei are critical. Low temperatures can make some $^7$Be, but the rates for other reactions on $^7$Be and $^{11}$C are relatively slow at these temperatures. At higher temperatures, metal production is inhibited by the lower concentration of $^7$Be, which is readily destroyed by the energetic thermal photons in the high temperature clump. However, reactions on $^{11}$C are more rapid at these temperatures, and so metal production decreases less
steeply at higher temperatures. For intermediate temperatures, $^7\text{Be}$ production is maximized, which in turn maximizes the metal production. For many parameter combinations, $T_g = 0.6$ provides the optimum temperature for metal production.

In cases with the largest metal production, it is the increase in the density due to jet mass deposition which allows the metal abundances to attain relatively high levels. If the abundances of CNO nuclei can become concentrated enough so that protons are consumed, the final ratios of CNO to $^1\text{H}$ can approach solar levels.

Due to momentum absorption by the jet, a dramatic increase in the clump density comes at the cost of sweeping up the clump in the jet. Therefore, the results we show with large density increases are more realistic for the parameter combinations which take as little time as possible to reach equilibrium abundances. In this way, even if the clump is swept up by the jet, the processing may still be able to occur before the clump leaves the hot central region of the quasar.

In the next chapter, we make some conclusions regarding our model and suggest other implications of the processes which occur in jet-clump nucleosynthesis.
CHAPTER 5

Conclusions

In this chapter we present final remarks concerning the relevance and applicability of the jet-clump model.

5.1 Range of Application for the Jet–Clump Model

Metal production in the jet-clump model varies greatly depending on the conditions assumed. Final CNO abundances approaching solar levels are attainable only for the highest densities and for a narrow range of temperatures. Also, in order to achieve significant final metal concentrations, the clump density must experience a drastic increase due to mass deposition by the jet. Finally, cases with the shortest time scale for metal production generate the most metals for the lowest energy jets.

Our model can create high concentrations of metals only in a small region of parameter space. The most restrictive parameter is the temperature. As explained before, this is due to the relative fragility of the $^7$Be nucleus, whose destruction reaction increases steeply with temperature.
When the jet mass deposition causes the density of the clump to increase far above its original value, the velocity of the clump eventually approaches that of the jet. Therefore long processing times in such cases are not realistic, because the clump is carried away by the jet and is removed from the hot, inner region of the quasar. Furthermore, sustained buildup of mass in the inner quasar region (as may occur for large clumps with \( d = l = 10^{13} \text{ cm} \)) is not likely, because the total mass of material in the BLR at any one time is only about 10 solar masses.

In the cases where solar or higher ratios for CNO are produced, much of the enhancement is due to the depletion of the protons in the clump. If this metal enriched material is subsequently mixed with other primordial material (which contains 93% hydrogen), the CNO concentrations will be diluted.

The extreme temperature and density conditions of the quasar environment represent an enticing opportunity for generating metals outside the standard stellar mechanisms. Our exploration of the jet-clump model represents a first order attempt at exploiting these unique conditions. Metal production through the processes in our model can be very rapid, but solar levels are achieved only for a select region of parameter space. Therefore, we find that metal production via a single pass through the processes of the jet-clump model is not likely to explain the the highly metal enriched state of quasar gas.
5.2 Implications of Low Level Metal Production

Although our model is not likely to fully account for the metal enrichment of the quasar environment, the presence of very low metal concentrations may still play an important role in explaining quasar abundances.

The standard picture used to explain the enhanced metals in quasars involves the stellar processing of gas in the quasar host galaxy during a burst of star formation and evolution. Some stars, for example, undergo a period of mass loss, in which enriched gas escapes the star and is returned to the surrounding environment. However, most of the early metal enrichment in quasars (and elsewhere) comes from the supernova of massive stars. The lifetimes and metal production capacities of these massive stars are important, because the stellar production scenario must bring the metals to solar or higher levels within $10^9$ years. As mentioned in Section 2.4, models which meet this time constraint use parameters for stellar evolution which are at the limits of their estimated ranges.

Recent work by Weaver (1997) suggests that the nucleosynthesis yields and lifetimes of massive stars may be highly dependent on the initial metallicity of the gas from which the stars are formed. A higher metallicity corresponds to a higher opacity, which in turn affects other issues in the evolution such as the strength of convective mixing within the star, and the amount of matter which falls back onto the core after the supernova explosion. The nucleosynthetic yields for the supernova are found to depend on the initial metallicity. Massive stars with low metallicities do not generate
as much metal output as do their higher metallicity counterparts. The dependency is particularly strong for metallicities near primordial levels.

The final metal concentrations for CNO in our model exceed primordial values for much of parameter space. Recall that primordial ratios of CNO to $^1$H are around $10^{-15}$ or less. If the first generation of stars which formed in the quasar environment included some material processed by jet-clump interactions, then the resulting nucleosynthesis could be enhanced. Higher metal yields per supernova could assist the stellar models for quasar metal generation by decreasing the time required for solar levels to be reached.

Unfortunately, no further work seems to have been done in this area, and detailed information is not available in Weaver (1997). Therefore, we mention this possibility briefly, but with withhold bolder claims pending more comprehensive studies.

5.3 Future Directions

5.3.1 More Reaction Rates and Heavier Nuclei

Since many of the scenarios presented in Chapter 4 produce significant pileup at $^{24}$Mg, the end point of our reaction network, a worthwhile next step would be to extend the reaction network to higher masses. Emission from heavier elements such as Si and even Fe are also observed in quasar spectra. The jet-clump model may be able to generate some of these species as well.
5.3.2 Variation of the Temperature

All the production scenarios presented in Chapter 4 show results for a fixed temperature. Only specific temperatures (usually $T_g = 0.6$) result in substantial abundance production.

Another exciting possibility for the jet-clump model would be to test the evolution in cases where the temperature is not constant, but decreases as the clump is removed from the hot, central quasar region. In this way, a clump which starts at an initially very high temperature will always pass through the effective metal production temperature.

A full implementation of this idea would require that the temperature evolution be carefully characterized. In a simple, preliminary test of this idea, we start with a clump at an initial temperature of $T_g = 1.0$, and set all other variable parameters to those used in Case C in Chapter 4. The evolution is allowed to go for only 20 days, which is roughly 10% of the total needed to reach the maximum final density of $10^{21}$ particles/cm$^3$. The final abundances for this situation are used as the initial abundances for another 20 day simulation at $T_g = 0.9$. In a similar pattern, the evolution is examined in 20 day intervals for temperatures down to $T_g = 0.2$. Final CNO abundances are roughly 2 orders of magnitude below solar levels, but are far larger than primordial abundances. The evolution levels off at $T_g$ below 0.3, partly because the reaction rates are much slower there, but mostly because the maximum density has been reached. The use of a more sophisticated approach to variation in temperature may increase the applicability of the jet-clump model.
5.3.3 Use in Chemical Evolution Models

Another possible way to enhance the production of the jet-clump model would be to allow material to experience jet-clump processes multiple times. Since the time scale for low level metal production is often very short, any fraction of clump gas which is exposed to multiple cycles of the jet-clump processes could be enriched according to the number of exposures. The lifetimes of quasar jets are estimated to be on the order of $10^8$ years (Norman & Scoville 1988), and so continuous, low level production over this time period could be significant. Our current work does not involve a chemical evolution model for quasars, but this would certainly be an useful extension of the model.

5.3.4 Spallation of High Energy Jets

Finally we present one interesting consequence of the jet-clump reactions: the possibility to convert a large fraction of $^4\text{He}$ from the jet into $^3\text{He}$ and D (D is an another symbol for $^2\text{H}$). Because the yields of jet-clump reactions are independent of the temperature of the gas into which the jet penetrates, this process may apply in regions other than the central quasar environment. In fact, $^3\text{He}$ and D are easily destroyed in high temperature gas, so spallation production is expected to be important in places with relatively low temperatures.
The generation of large amounts of D in this way would be especially interesting, since it is currently thought that a significant amount of D is produced only in big bang nucleosynthesis (Rolfs & Rodney 1988). Also, the chemical evolution of $^3\text{He}$ has been scrutinized recently due to the debate (Hata et al. 1995; Copi, Schramm, & Turner 1995) over the concordance of estimated primordial light element abundances (i.e., $^4\text{He}$, $^3\text{H}$, D, $^7\text{Li}$) with big bang nucleosynthesis yields.

Particle jets are known to exist around quasars. Other candidate sites for particle acceleration include the ejecta of massive stellar supernovae. Ramaty, Kozlovsky, & Lingenfelter (1997) go so far as to suggest that an acceleration mechanism in supernovae may be required to explain the galactic abundances of Be and B, which are thought to result from spallation$^1$ of CNO on $^1\text{H}$ and $^4\text{He}$.

We briefly present here results describing the $^3\text{He}$ and D production for the case of a monoenergetic $^4\text{He}$ jet impinging on and stopping within a cloud of primordial material. The cloud contains $1\ M_\odot$ of material, while the total jet mass is of order $10^{-2}\ M_\odot$. Only the jet-clump reactions on $^4\text{He}$ projectiles as listed in Table 3.6 are utilized, and no thermonuclear reactions processes are included. Figure 5.1 shows the final ratios of $^3\text{He}$ and D with respect to $^1\text{H}$ for beams of different energies. The final abundance ratios increase at higher beam energies because the yields of the jet-clump reactions also increase for higher $^4\text{He}$ energy. For incident $^4\text{He}$ energies above about 800 A MeV, the destruction of the incident $^4\text{He}$ beam is nearly complete. This is in accordance with the survival fraction depicted in Figure 3.10b, which indicates that

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$^1$Spallation refers to the process by which energetic, relatively heavy nuclei such as $^{12}\text{C}$ collide with interstellar gas and are subsequently broken up into lighter nuclei such as Be or B.
Figure 5.1: Production of $^{3}\text{He}$ and $^{2}\text{H}$ by jet-clump reactions (numbers 7 through 14 in Table 3.6) when $10^{-2} \text{ M}_\odot$ of $^{4}\text{He}$ is injected into and stopped by 1 $\text{ M}_\odot$ of primordial (93% $^1\text{H}$, 7% $^4\text{He}$) material which is too cold to sustain thermonuclear reactions. The curves represent final ratios of $^3\text{He}$ and $^2\text{H}$ to $^1\text{H}$ for various incident energies of the $^4\text{He}$ jet. Conversion of the incident jet is nearly complete for energies above 800 A MeV.
for a high energy jet of $^4\text{He}$ incident on primordial gas, only a small fraction of the incident projectiles survive to be deposited in the stopping material. For $^4\text{He}$ jet energies above 800 AMeV, different relative amounts of $^3\text{He}$ and D can be created, but the sum of all destruction reactions leading to D or $^3\text{He}$ is nearly constant above this energy.

In the scenario presented in Figure 5.1, converted jet material is diluted by a factor of 100 with the surrounding material. Even so, for jet energies greater than about 400 AMeV, the final abundance of $^3\text{He}$ and D are both a factor of 10 higher than their primordial values. Also, it is interesting to note that $^3\text{He}$ is a factor of 2 more abundant that D, a ratio mimicking that produced by primordial nucleosynthesis.

No destruction processes were included for the $^3\text{He}$ or D. Since a significant fraction of the incident $^4\text{He}$ is destroyed as it slows down, much of the more fragile products may also be destroyed. Since $^3\text{He}$ and D are produced mainly in reactions sharing the total energy among three or more products in the exit channel, the energies of each product will be significantly lower that of the incident projectile. Therefore, the low energy portion of Figure 5.1 would not change much when $^3\text{He}$ and D destruction processes are included, but the high energy region may be substantially reduced.

A more detailed analysis concerning this application of jet–clump reactions will soon be available in Vandegriff, Boyd, & Kajino (1997).
5.4 Final Remarks

We thus conclude our presentation of the jet–clump interaction model for metal generation in quasars. The most striking aspect of our model is the short amount of time required to generate low level metal abundances. Although the conditions in the quasar environment are such that some gas may experience processing as described in our model, the amount of enrichment in a single pass for most parameter combinations is well below solar levels. Metal production substantially above primordial values may be possible for a wide range of conditions, especially if the temperature is initially high and passes through $T_9 = 0.6$ as the clump cools. Furthermore, low level production may be important in the chemical evolution of quasars. Jet–clump interactions offer an interesting way to produce metals in the unique conditions offered by the central quasar environment.
BIBLIOGRAPHY


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Burbidge G., & Burbidge M. 1967, Quasi-Stellar Objects (San Francisco: W. H. Freeman)


Cairns, D. J., Griffith, T. C., Lush, G. J., Metheringham, A. J., & Thomas, R. J. 1964, Nucl. Phys., 60, 369


Caughlan, G. R., & Fowler, W. A. 1988. Atomic Data and Nuclear Data Tables, 40, no.2, 284


153


Kawano, L. 1989, FERMI LAB-PUB-88/34-A.


Kolb, E. W., & Turner, M. S. 1990, The Early Universe, (Reading, Massachusetts: Addison-Wesley)


Marion, J. B., & Young, F. C. 1968, Nuclear Reaction Analysis: Graphs and Tables (New York: John Wiley & Sons)


Post, R. F. 1956, Rev. Mod. Phys., 28, 338


Schmidt, M. 1963, Nature, 197, 1040


Weaver, T. A. 1997, presentation given at Nuclei in the Cosmos IV, Notre Dame University, South Bend, IN, June 20-27, 1996

Weedman, D. W. 1976, QJRAS, 17, 227


