through roughly the same sequence of temperatures and radii as a function of time as it cools. We thus expect to get essentially the same r-process out of every supernova. This satisfies our expectations from the observations of the r-process elements in old stars (see Section 3.3).

Does a solar system distribution naturally emerge in such a wind? Meyer et al (1992), using a schematic model based on output from Wilson & Mayle (1993), found the resulting abundances matched the solar system distribution quite well (see also Howard et al 1993 and Takahashi et al 1994). A more detailed model, using mass element trajectories calculated directly in Wilson and Mayle's supernova code produced abundances that also agree well with the solar distribution (Woosley et al 1994). This latter model also gives the correct amount of r-process mass per supernova ($\sim 10^{-4} M_{\odot}$). Confirmation of nascent neutron star winds as the site for the r-process will require a full survey of the nucleosynthesis in detailed, realistic wind models. Nevertheless, nascent neutron star winds seem extremely promising as the site for the r-process.

4. THE s-PROCESS

> Must we, as Solon advises, always keep the goal in sight?
>
> Aristotle, *Nichomachean Ethics*

The s-process is the other major nucleosynthetic process that assembles heavy elements. We know that the s-process path in the neutron number–proton number plane crosses the neutron closed shells at the valley of beta stability. This tells us that the s-process occurred in an environment with a much lower neutron density than the r-process. Also, the s-process occurred over a much longer time period.

In this section we seek to understand how the s-process occurs. We then turn to the question of s-process sites. Finally we consider constraints on those sites.

4.1 *The s-Process Mechanism*

Because of the neutron densities and timescales inferred for the s-process from the abundance peaks, we can infer that the s-process is not a freeze out from equilibrium. Instead, it is a neutron-capture process that occurs in a system striving to reach equilibrium, but falling short of its goal. The main reactions carrying the bulk of the nuclei towards the iron group can liberate neutrons. Pre-existing seed nuclei capture these neutrons and produce the s-nuclei. The s-process is clearly a secondary process.

The dominant reactions that can liberate neutrons are $^{13}C(\alpha, n)^{16}O$ and $^{22}Ne(\alpha, n)\,^{25}Mg$. In these reactions, the neutron-rich isotopes, ^{13}C and ^{22}Ne give up their excess neutrons to heavier nuclei. At this point, we may ask where these excess neutrons came from in the first place. The answer to this interesting question illustrates an important point about the overall nuclear evolution of the universe.

The abundances that emerge from the Big Bang are roughly 90% by number ^{1}H and 10% ^{4}He (e.g. Walker et al 1991). This yields $Y_e = 0.88$. On the other hand, we may make the observation that ^{1}H and ^{3}He are the only proton-rich (that is, with proton number greater than neutron number) stable isotopes in nature. This means that in order for nature to put the nucleons in the universe into nuclei with the strongest binding energy per nucleon (iron-group nuclei), the Y_e of the universe must decrease.

Most of the decrease in Y_e comes from the weak decays in the p-p chains and the CNO cycle during hydrogen burning. These interactions drop Y_e from 0.88 to 0.5 in material that has completed hydrogen burning. ^{4}He itself does not have any excess neutrons, but some production of excess neutrons occurs in the CNO cycle due to reactions like $^{12}\mathrm{C}(p, \gamma)^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C}$. The net result is the conversion of a free proton into an excess neutron, and a drop in Y_e. The ^{22}Ne production builds up from abundant ^{14}N produced in the CNO cycle. The sequence is $^{14}\mathrm{N}(\alpha, \gamma)^{18}\mathrm{F}(\beta^+)^{18}\mathrm{O}(\alpha, \gamma)^{22}\mathrm{Ne}$. Here it is the fact that the only stable isotope of flourine is neutron rich that leads to a decrease in Y_e. We see that the excess neutrons in ^{13}C and ^{22}Ne are a consequence of the overall drive to decrease Y_e in stars. We must keep the goal of the nuclei in sight to understand where the excess neutrons come from that drive the s-process.

The first attempts to understand the details of the s-process led to the classical model. The neutron density is always low in the s-process (compared to the r-process). If a nucleus is unstable to β^- decay following neutron capture in the s-process, it will almost always β^- decay to the first available stable isobar before it can capture another neutron. Thus, it generally suffices in s-process studies to follow only the abundances as a function of mass number, which only change by neutron capture. In this approximation, the rate of change of the abundance N_A of nuclei with mass number A is

$$\frac{dN_A}{dt} = -n_n \langle \sigma v \rangle_A N_A + n_n \langle \sigma v \rangle_{A-1} N_{A-1}, \tag{9}$$

where n_n is the neutron number density and $\langle \sigma v \rangle_A$ is the thermally averaged neutron-capture cross section for the stable isobar of mass number A. We can write $\langle \sigma v \rangle_A$ as $\sigma_A v_T$, where v_T is the thermal velocity of neutrons and σ_A is an average cross section, given in terms of v_T. With the definition of the neutron exposure

$$\tau = \int n_n v_T dt, \tag{10}$$

we find

$$\frac{dN_A}{d\tau} = -\sigma_A N_A + \sigma_{A-1} N_{A-1}. \tag{11}$$

Note that the neutron exposure τ is a fluence. It has units of inverse millibarns (1 barn = 10^{-24} cm^2). Because it is a neutron flux integrated over time, it is an appropriate evolutionary parameter for the s-process. If the s-process achieves a steady state, then $dN_A/d\tau \rightarrow 0$ and $\sigma_A N_A \rightarrow$ constant.

Clayton et al (1961) were able to show that a single neutron exposure τ could not reproduce the solar system's abundance of s-only nuclei. Seeger et al (1965) showed that an exponential distribution of exposures, given by

$$\rho(\tau) = \frac{f N_{56}}{\tau_0} e^{-\tau/\tau_0}, \tag{12}$$

where f is a constant and N_{56} is the initial abundance of ^{56}Fe seed, did reproduce the solar distribution of s-nuclei. For the distribution of exposures given in Equation (12), Clayton & Ward (1974) found that for an exponential average of flows in the s-process

$$\sigma_A N_A = f N_{56} \tau_0 \prod_{A'=56}^{A} [1 + (\sigma_{A'} \tau_0)^{-1}]^{-1}. \tag{13}$$

A fit to the empirical $\sigma_A N_A$ for s-only nuclei then gives the quantities f and τ_0.

A complication to the above classical model is the branching that occurs at certain isotopes. Here it may be that the β^- decay rate is not considerably greater than the neutron-capture rate. In some cases the nucleus may β^- decay before neutron capture and in others it may neutron capture before suffering β^- decay. The assumptions leading to Equation (9) thus break down. Ward et al (1976) developed an analytic treatment of branching in the case of a time-independent neutron flux. For time-dependent neutron fluxes, it is necessary in general to solve a full network of nuclei numerically (e.g. Howard et al 1986). Since the s-process branchings will in general be temperature and neutron density dependent, s-nuclei branchings are important diagnostics of the environment in which the s-process occurred. We will see this in more detail in Section 4.3.

4.2 *s-Process Sites*

To obtain a good fit of the σN curve to the solar system s-process abundance distribution, three distinct exponential distributions of neutron exposures may be necessary (Clayton & Rassbach 1967, Clayton & Ward 1974). One exposure, with $\tau_0 \approx 0.30$ mb^{-1}, produces most of the nuclei in the mass range $90 < A < 204$. This is the main component. Another exposure, with $\tau_0 \approx 0.06$ mb^{-1} contributes to the $A \lesssim 90$ s-nuclei abundances. This weak component is required in order to explain the σN curve around $A \sim 90$. These two components indicate that two separate sites contributed to the abundance of solar s-nuclei. Finally, a strong component, with $\tau_0 \approx 7.0$ mb^{-1}, may be necessary to explain the abundances of the A = 204–209 nuclei. One possible explanation of this component is that the distribution of exposures in the main component is not exactly exponential, but rather is higher than exponential at large τ. There is probably no need for a separate site for the strong component of the s-process.

The weak s-process component likely comes from He burning in the cores of massive stars ($\gtrsim 15 M_{\odot}$) (Truran & Iben 1977, Lamb et al 1977), where the temperature is high enough for the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ reaction to produce a substantial amount of neutrons. These stars also have strong winds that eject this material into the interstellar medium. Recent work has confirmed the plausibility of this site (Arnett & Thielemann 1985, Busso & Gallino 1985, Prantzos et al 1987, Langer et al 1989, Raiteri et al 1991a, Baraffe et al 1992). Uncertainties in the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ and $^{22}\mathrm{Ne}(\alpha, \gamma)^{26}\mathrm{Mg}$ reaction rates prevent us from predicting the neutron exposure in these models to high accuracy. Recent results on these rates may indicate that the s-process is somewhat more robust in this site than previously thought (e.g. Baraffe & El Eid 1994). This may complicate the separation of the $A \lesssim 90$ s-nuclei into those coming from the weak and main components.

Some s-processing may also occur in core carbon burning or shell helium burning in massive stars. This has been studied by Arcoragi et al (1991) and Raiteri et al (1991b). The results indicate that this processing does not contribute in a significant way to the weak component.

The main component of the s-process is likely to occur in the helium-burning shell in asymptotic giant branch (AGB) stars (Weigert 1966, Schwarzchild & Härm 1967, Ulrich 1973). The structure of such a star is an inert carbon-oxygen core, on top of which lies a convective helium-burning shell. On top of this helium-burning shell is the hydrogen-rich envelope, which itself is convective. The original idea was that the convective helium shell might reach out far enough into the hydrogen-rich envelope that protons and $^{12}\mathrm{C}$ (the result of helium burning) could mix and produce $^{13}\mathrm{C}$, as discussed in Section 4.1. The $^{13}\mathrm{C}$ would then be the source of neutrons for the s-process. [The current picure is that convection does not provide the mixing, but that protons reach down into the carbon-rich shell by diffusion or semiconvection (see below).]

An attractive feature of this model is the fact that the helium burning occurs in pulses. Between pulses, hydrogen burns quiescently in a thin shell. Once the supply of helium from the hydrogen burning builds up, a helium-burning pulse occurs. The energy liberated expands the star and shuts off the hydrogen burning. After the pulse has occurred, the star settles down again and begins hydrogen-shell burning anew. Pulses last of order tens of years while the interpulse periods are of order thousands of years. The significance for the s-process is that there is an overlap of mass zones experiencing successive helium-buring pulses. Ulrich (1973) was able to show that the mixing and burning sequence could naturally give rise to an exponential distribution of neutron exposures. Alternating overlap of convection zones can carry the newly produced s-nuclei into the envelope (the so-called "third dredge up"). These nuclei would then find their way into the interstellar medium via winds or by the ejection of the atmosphere in a planetary nebula phase.

This nice model for the s-process suffered a setback when Iben showed that an entropy barrier prohibited mixing of protons into the helium shell (Iben 1975a,b, 1976). It was then proposed instead that $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ be the source (e.g. Iben & Renzini 1983). The helium core grows by accreting the ashes of the hydrogen-burning shell. The products of CNO burning are ^{4}He and ^{14}N in that shell, which combine to give ^{22}Ne early in helium burning, as discussed in Section 4.1. The $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction then drives the s-process. The pulse and mixing that occurs gives an exponential distribution of neutron exposures. This model has some difficulties, however. Basically, the shell flashes in most AGB stars are not hot enough to liberate most of the ^{22}Ne neutrons, and the massive ABG stars that are hot enough are too rare. This has led workers to consider alternative neutron sources in low-mass AGB stars ($M < 3M_{\odot}$).

In low-mass AGB stars, the temperature is too low in the helium-burning shell for the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction to be the major source of neutrons. Iben & Renzini (1982) argued, however, that, despite the entropy barrier to convection, semiconvection or diffusion could cause the mixing of protons with ^{12}C in the interpulse period. This produces pockets of ^{13}C atop the He zones which can liberate neutrons during convective ingestion by the next pulse. Recent work indicates that this is a promising site for the s-process (Gallino et al 1988; Boothroyd & Sackmann 1988a,b,c,d; Hollowell & Iben 1988; Käppeler et al 1990). In particular, these models seem to give a good fit to the main component of the solar σN curve (e.g. Käppeler et al 1990). We must note that these s-process calculations are post-processing calculations, which means that the neutron density is a parameterized quantity. Even more serious is the lack of a demonstrated occurrence of the needed ^{13}C-rich pocket, which is therefore taken on faith at the present time. It remains to be seen whether the good agreement with the solar s-process abundances will hold up when the s-process calculations are directly coupled to complete stellar models. Such coupled calculations may be available in the not-too-distant future. It will also be important to include the effects of energy generation by all the nuclear reactions on the stellar structure (Bazan & Lattanzio 1993).

4.3 *Constraints on s-Process Sites*

What constraints can help to evaluate the proposed sites discussed in the previous section? s-process branchings are the first important constraints. The likelihood that a beta-unstable nucleus in the s-process beta decays depends on the rate of beta decay compared to the rate of neutron capture. Evidence for branching provides information about these rates. In particular, with knowledge of the beta-decay rate from laboratory experiments, the degree of branching constrains the neutron capture rate $n_n\langle\sigma v\rangle$. Then knowledge of $\langle\sigma v\rangle$ from the laboratory constrains n_n, the neutron number density during the s-process. On the other hand, if the beta-decay rate is temperature sensitive (e.g. Takahashi & Yokoi 1987), branching data yield constraints on the temperature during the s-process. Branching data may also yield constraints on the mass density during the s-process through electron capture rates. Finally, branching data can constrain the duration of the neutron pulses (Ward & Newman 1978). If the pulse period were much shorter than the lifetime of the branching point isotope, there would be no branching. Pulses that were too long in duration would allow too much neutron capture.

What do we find for the s-process in nature? For the main component of the s-process, the isotopes ^{134}Cs, ^{148}Pm, ^{151}Sm, ^{154}Eu, ^{170}Yb, and ^{185}W are branch-point isotopes with potential as diagnostics of the temperatures and neutron densities prevailing during the s-process. Beer et al (1984) used ^{151}Sm, ^{170}Yb, and ^{185}W to find limits on the neutron number density and temperature. Uncertainty in the population of the 137 keV isomeric state in ^{148}Pm during the s-process makes conclusions from this isotope difficult. Uncertainties in cross sections and abundances limit the usefulness of ^{134}Cs and ^{154}Eu.

As for the mass density, Yokoi & Takahashi (1983) noticed that ^{163}Dy could beta decay in stars, even though it is stable on Earth. In stars, the ^{163}Dy atom is ionized so that in fact the daughter atom ^{163}Ho would be at slightly lower mass. ^{163}Ho then could either capture a neutron or electron capture back to ^{163}Dy. The electron capture rate depends on the density of electrons, which in turn depends on the mass density. Beer et al (1985) were able to constrain the mass density in the s-process in this way.

Finally, Beer & Macklin (1988) studied ^{151}Sm in order to determine a lower limit to the duration of the neutron pulse in the s-process. Studies of ^{86}Kr may give an upper limit to the pulse duration (Beer & Macklin 1989). Unfortunately the weak component in this region introduces ambiguities into such an analysis.

The net results of branching studies in the context of the classical model give a temperature for the main component of $2.8\text{–}3.9 \times 10^8$K, a neutron density of $2.3\text{–}4.5 \times 10^8 \text{cm}^{-3}$, a mass density of $2.6\text{–}13 \times 10^3 \text{g cm}^{-3}$, and a pulse duration of greater than 3 years (Käppeler et al 1989). These numbers agree reasonably well with those expected from stellar models. A similar analysis for the weak component yields a temperature of $1.8\text{–}3.0 \times 10^8$K and a neutron density of $0.8\text{–}1.9 \times 10^8 \text{cm}^{-3}$ (Käppeler et al 1989).

The relatively high temperatures found in this analysis for the main component suggest that $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ is the neutron source for the s-process. Howard et al (1986) studied the s-process nucleosynthesis with this neutron source. They obtained poor fits to the solar σN curve when they used parameters derived from stellar models. In particular, the average neutron density during the pulses was too high to reproduce the correct branchings. Busso et al (1988) have confirmed these results. On the other hand, the high temperature ^{22}Ne source may simply be the last hot part of the neutron burst that was primarily from ^{13}C at lower temperature (see below).

Let us consider now the evidence from observations of stars. It was the observation of technetium in certain red giant stars (Merrill 1952) that showed that stars do indeed synthesize elements and led Cameron (1955) to work out many of the details of the s-process. Since all isotopes of Tc are unstable, any Tc present in the surface of a star must have been synthesized in the interior of the star by the s-process and then dredged up to the surface. Recent observations show that red giant stars in the solar neighborhood that do have s-process abundance enhancements in their atmospheres do not show the accompanying enhancements of ^{25}Mg and ^{26}Mg that one would expect from alpha capture on ^{22}Ne (e.g. Smith & Lambert 1986, McWilliam & Lambert 1988). In addition, observations of Rb and ^{96}Zr constrain s-process branching at ^{85}Kr and ^{95}Zr. Astronomers find that the s-process occurring in the interiors of the stars observed must be happening at low neutron densities ($n_{\mathrm{n}} \lesssim 10^9\mathrm{cm}^{-3}$), not the high neutron densities characteristic of the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ reaction (e.g. Lambert 1993).

From this evidence, it appears that ^{13}C is more promising as the source of s-process neutrons, indicating that low-mass AGB stars are probably the site of the s-process. Such stars give a low temperature s-process ($\sim 1.5 \times 10^8$K) which would seem to contradict the higher temperatures found from the analysis of the s-process branchings in the classical model ($T = 2.8$–3.9×10^8K) discussed above. In the low-mass AGB star s-process calculations that do show good agreement with solar abundances (e.g. Gallino et al 1988, Käppeler et al 1990), there are two bursts of neutrons per pulse: a strong burst due to the $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{C}$ reaction at $T \sim 1.5 \times 10^8$K, and a second, weaker one, due to the $^{22}\mathrm{Ne}(\alpha, n)^{25}\mathrm{Mg}$ reaction. This weaker burst occurs when the helium shell contracts following the first burst and heats to a temperature of $T \sim 3 \times 10^8$K. It resets the branch-point thermometers to this higher temperature, in agreement with the analysis from the classical model.

More evidence for ^{13}C as the dominant source for neutrons in the s-process comes from studies of galactic abundance evolution. Mathews et al (1992, 1993) studied the evolution of the Ba/Fe ratio in our Galaxy. Ba is predominantly an s-process element and hence must be secondary (i.e. made from initial Fe). Mathews et al found that only an s-process behaving as a primary process fit well the observations of Ba abundances in the atmospheres of old stars. ^{13}C is a primary neutron source, as discussed in Section 3.3. ^{22}Ne is secondary because it must be built up from pre-existing CNO nuclei. The Fe seeds are of course secondary. Clayton (1988a) described how the secondary s-process with the ^{13}C neutron source is able to mimic primary nucleosynthesis. The idea here is that while the galactic abundance of Fe seed for the s-process grows with time, so does the abundance of s-process neutron poisons.

A final point of increasing relevance is the new information from pre-solar SiC grains found in the Murray and Murchison meteorites. These grains are carriers of isotopic anomalies in s-process isotopes (Srinivasan & Anders 1978, Tang & Anders 1988). In addition, these grains are anomalous in their Si and C (Zinner et al 1987, Anders & Zinner 1993). It appears that these grains have condensed in carbon-star atmospheres, which are s-process enriched and have variable ^{13}C-rich compositions (Lambert et al 1986). As surviving stardust, the grains are almost pure endmembers in the "cosmic chemical memory" theory for interpreting isotopic anomalies in solar system samples (Clayton 1978, 1982). From studies of trace s-isotopes in these grains (Ott & Begemann 1990 a,b; Zinner et al 1991; Richter et al 1992; see Anders & Zinner 1993 for a review) the abundance ratios only fit if the grains come from low-mass AGB stars (Gallino et al 1990). A vexing problem with this idea, however, is that such stars cannot explain the anomalous Si isotopes (a major constituent of the grains). One suggested answer is higher mass AGB stars, in which burning of Mg isotopes in late pulses resets the ratio of ^{29}Si/^{30}Si(Brown & Clayton 1992). Galactic abundance evolution of Si isotopes may also hold the key (Clayton 1988b, Gallino et al 1994). Alternatively, some other site may be responsible for these grains (e.g. Arnould & Howard 1993). These tiny, sturdy grains have traveled from afar carrying important messages about the s-process which have yet to be deciphered.

In summary, low-mass AGB stars are at present the most promising site for the main component of the s-process. Confirmation of this site will require continued interplay of nuclear physics, meteoritics, stellar evolution and structure theory, nucleosynthesis theory, galactic abundance evolution theory, and stellar astronomy. Many people will be busy for quite some time to come!

5. THE p-PROCESS

> . . . and the elements shall melt with fervent heat . . .
>
> II Peter 3:10

We turn finally to the p-nuclei. These are the 35 nuclei bypassed by the r- and s-processes. As we see from Figure 1, except for the light p-nuclei (^{92}Mo, ^{94}Mo, ^{96}Ru, ^{98}Ru), the abundances of p-nuclei are considerably less than those of their r- and s-nuclei counterparts. Furthermore, the p-process abundance distribution shows interesting structure with peaks at ^{92}Mo and ^{144}Sm. These are important clues for determining where the p-process occurs.

It is probably wrong to think that the p-process occurs in a single site. We can imagine many astrophysical settings where conditions are right to modify a pre-existing supply of r- and s-nuclei to form p-nuclei. The relevant question is really what site contributes the bulk of the p-nuclei. For more details on the p-process, the reader should consult the excellent review by Lambert (1992).

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THE r-, s-, AND p-PROCESSES IN NUCLEOSYNTHESIS

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1. INTRODUCTION

Burbidge et al (1957) and Cameron (1957) laid out the framework for our understanding of the formation of the heavy nuclei (those nuclei with mass number $A \gtrsim 70$). From systematics in the solar system abundance distribution, Burbidge et al determined that the heavy nuclei were formed in three distinct nucleosynthetic processes, which they termed the r-, s-, and p-processes. That we still use these terms today is a credit to the soundness of this work done 37 years ago.

We may understand how Burbidge et al and Cameron arrived at their conclusions from Figure 1. One population of nuclei, the s-nuclei, shows an abundance distribution with peaks near mass numbers 87, 138, and 208. These nuclei are made in a *slow* neutron-capture process, the s-process. A *rapid* neutron-capture process, the r-process, is responsible for the r-nuclei, whose abundance distribution shows peaks at mass numbers 80, 130, and 195. The p-process is responsible for production of the rarer, more proton-rich heavy isotopes (the p-nuclei) that cannot be made by neutron capture.

The first quantitive evaluations of the ideas of Burbidge et al and Cameron came to light in the early 1960s with work on the s-process (Clayton et al 1961, Seeger et al 1965) and the r-process (Seeger et al 1965). These calculations further elucidated the mechanisms for heavy-element formation and showed the plausibility of the framework developed in the 1950s. Subsequent work has focused on determining the astrophysical sites where the r-, s-, and p-processes occurred with the help of improved nuclear details, stellar models, and abundances. A goal of this paper is to review the recent progress astrophysicists,

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