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A SEARCH FOR r-PROCESS ELEMENTS IN THE VELA SUPERNOVA REMNANT[1]

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ABSTRACT

After a description of recent developments in the physics of rapid neutron capture in Type II supernovae and a discussion of the detectability of supernovae ejecta, we present the data from a search for Ge, Kr, Yb, Os, and Hg in five stars behind or within the Vela remnant. Only Ge II was detected, but its column density and the upper limits of the other species show no excess above the estimated contribution of ambient gas. Finally, we discuss the extent that clumping and the improved performance of the GHRS may make r-process ejecta from Vela detectable in the future.

Subject headings: ISM: abundances — nuclear reactions, nucleosynthesis, abundances — supernova remnants — ultraviolet: stars

1. INTRODUCTION

Supernovae have long been thought to be the site of rapid neutron capture nucleosynthesis (hereafter r-process; Burbidge et al. 1957; Cameron 1957). This nucleosynthesis process is responsible for the production of many of the neutron-rich nuclides heavier than iron. The Type II supernova explosion environment remains the leading candidate for an r-process production site, since the weak interaction dynamics attending the gravitational collapse process produces the neutron-rich conditions conducive to r-process nucleosynthesis.

An attractive prospect for confirming Type II supernovae as the most probable sources of r-process material is to observe an enhancement of certain elements in the immediate vicinity of a known event. The Vela supernova remnant (SNR) is perhaps the most suitable environment to investigate, since behind or within this SNR there are many, fairly bright B-type stars that can be used as sources for finding absorption lines arising from interstellar gases. This remnant shows up as a nearly circular patch of X-ray emission 7°.3 in diameter (Aschenbach 1993) centered on the Vela pulsar, a prominent radio source (Rishbeth 1958), and a large network of filaments in the visible (first recognized by Melotte 1926). Its age, $t_0 = 11{,}200$ yr (Taylor, Manchester, & Lyne 1993), is about ideal for the study of absorption lines. Much younger SNRs have material moving so fast that the lines are very broad and thus harder to detect, e.g., as with SN 1006 investigated by Wu et al. (1993). If the remnant is considerably older than 10^4 yr, the dilution with ordinary gas becomes too severe, as we show later.

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2. THE MODERN "r-PROCESS"

While the actual site in the supernova where r-process nucleosynthesis takes place is still uncertain (Mathews, Bazan, & Cowan 1992; Cowan, Thielemann, & Truran 1991), there has been considerable recent excitement over the proposal by S. E. Woosley and collaborators (Woosley & Hoffman 1992; Meyer et al. 1992; Woosley et al. 1994) that neutrino-heated neutron-rich ejecta from the postsupernova explosion "hot bubble" environment may be the r-process site. This site produces about the right amount of material with an abundance yield that is in excellent agreement with the solar system abundance distribution.

The "hot bubble" is the region above the protoneutron star which forms a few seconds after the bounce of the supernova core. The prompt shock produced by the core bounce process is degraded in energy because of nuclear photodissociation and becomes an accretion shock. This shock is reenergized by the intense neutrino flux (luminosities for each neutrino species are $L_\nu \sim$ a few $\times\ 10^{52}$ ergs s^{-1}) emergent from the protoneutron star. The shock reheating process takes place on a timescale of order a few tenths of a second, and subsequently the shock moves out, producing the supernova explosion.

After the supernova explosion we are left with a hot protoneutron star which is still deleptonizing (i.e., neutrinos are diffusing out). The neutrino diffusion timescale is of order 10 s. Between about 3 s and 15 s after core bounce the neutron star is surrounded by a low-density quasi-hydrostatic envelope: the "hot bubble." The material in this envelope is heated by neutrino interactions. In fact, this material is heated to the point where it is a relativistic electron-positron pair-dominated plasma.

Neutrino heating causes the material in this envelope to expland slowly. Eventually, the material escapes to infinity. In fact, the envelope material flows out in a neutrino-driven "wind." This "wind" persists for about 10 s.

The baryons in the hot bubble material are in the form of free neutrons and protons near the neutron star surface where the temperatures are comparable to the neutrino-sphere temperature, $T_\nu \sim 5$ MeV. As the material flows out in the wind its temperature drops. For temperatures $T > T_{eq} \sim 0.75$ MeV the material is in nuclear statistical equilibrium.

As the material flows out beyond a radius of about 100 km its temperature drops below T_{eq} and it "freezes out" of nuclear statistical equilibrium. The nucleosynthesis produced in such a freeze-out process depends on three parameters: the entropy per baryon, the neutron-to-proton ratio, and the material expansion timescale. All three of these parameters are set by the neutrino flux from the neutron star. Neutrino heating ensures relatively high entropy and neutron-rich conditions which are very promising for the production of neutron-rich nuclides in the freeze-out process. Meyer (1994) has discussed this nucleosynthesis process in detail.

There are many aspects of this picture for r-process nucleosynthesis which remain uncertain. For example, we expect the region about the neutrino sphere to be convectively unstable soon after core bounce (Herant, Benz, & Colgate 1992). If this convection persists into the r-process epoch, then the picture of nucleosynthesis outlined above might require alteration. In any case, this site for r-process nucleosynthesis is completely dominated by neutrinos. New neutrino physics may translate into significant alterations in r-process nucleosynthesis yields (Qian et al. 1993). In particular, the ratio of light-to-heavy r-process elements may be sensitive to the physical conditions Furthermore, it is clear that nucleosynthesis yields from the hot bubble region may be sensitive to many of the parameters which describe the post–core-bounce supernova environment, such as the neutrino luminosity history, the entropy, the velocity field, etc. Some nucleosynthesis modelers find excellent agreement between their calculated r-process yields (Woosley et al. 1994) and the observed solar system distribution of these nuclides (at least away from the $N = 50$ neutron closed shell), while others do not (Witti 1993). Their calculations show that nucleosynthesis can become a probe of the supernova environment in the epoch immediately following core bounce. The sensitivity of the abundance ratio of the heaviest observable r-process species, as exemplified by Os, the lightest species, as exemplifed by Ge and Kr, to depth in a supernova model is shown by Figure 15 of Woosley et al.

There is already some evidence from the Ultra Heavy Cosmic Ray Experiment that for nuclei with $Z \geq 74$ an r-process enhancement over solar system abundances has been found (Thompson et al. 1993). However, direct observations of r-process elements in an SNR could provide insight into the location of r-process production and might provide constraints on the physics of the hot bubble and new neutrino physics. Unfortunately, most of the r-process elements are difficult to observe in their dominant state of ionization at optical wavelengths. However, some r-process elements have lines in the ultraviolet where they are observable with the *Hubble Space Telescope* and the Goddard High Resolution Spectrograph (GHRS) (Cardelli 1994).

3. THE DETECTABILITY OF EJECTA

For our observations to yield a useful result two criteria must be met. First, when spread over the surface of a sphere whose radius is a nonnegligible fraction of the remnant's radius, the column density of r-process material from the supernova must exceed our detection threshold. Second, the enhancements of the observed r-process elements must be large enough to distinguish them from the background arising from foreground gas or ambient gas with which the ejecta have been mixed.

Material ejected by the supernova collides with an intercloud medium of characteristic density ρ_i and starts a spherical blast wave that sweeps up a surface density at a distance r given by

$$\sigma_i = \frac{r\rho_i}{3}, \quad (1)$$

which will cause an initial dilution of the ejecta.

As long as the ejecta are contained within the blast wave, they will be invisible because of the very high ionization and velocity dispersion of this gas. However, as soon as the blast wave moving at the velocity v_b hits an interstellar cloud of any appreciable density ρ_c, the material will mix with gas on the cloud's front surface. Eventually, it will show up in a zone of radiatively cooled material that accumulates behind a secondary, slow shock that propagates through the cloud. The velocity of this cloud shock v_c is, to within a factor not much different from unity (McKee & Cowie 1975), given the relation

$$v_c = \left(\frac{\rho_i}{\rho_c}\right)^{1/2} v_b . \quad (2)$$

After the gas has had a chance to cool radiatively behind the shock in the cloud to a temperature T ($\sim 10^4$ K) in a time $\tau(T, v_c, \rho_c)$, its velocity dispersion will be small and the gas will have mostly recombined. Under these circumstances, absorption lines from singly ionized or neutral atoms should become visible, moving at a radial velocity very slightly less than v_c times a projection factor cos θ for the line of sight. Interstellar components at moderate velocities (much less than v_b) have been identified in previous observations of the spectra of stars within and behind the Vela remnant (Jenkins, Silk, & Wallerstein 1976, hereafter JSW; Jenkins, Wallerstein, & Silk 1984). As the shock in the cloud sweeps through more material, there is some further dilution of the elements created by the supernova, giving rise to an additional surface density,

$$\sigma_c = \rho_c v_v \Delta t , \quad (3)$$

over a time interval Δt that we will define below.

The expansion of the primary blast wave while it is in the adiabatic phase is given by the power law for the growth of the remnant's radius with time in terms of the present radius r_0 and age t_0 (Sedov 1969),

$$r/r_0 = (t/t_0)^\eta , \quad (4)$$

where $\eta = 0.4$ for expansion in a homogeneous medium but increases to 0.6 in a medium whose density behind the blast wave is modified by cloud evaporation (McKee & Ostriker 1977). The velocity of the blast wave at the time it hits a cloud at a distance r_c from the explosion's center of expansion is given by

$$v_b = \frac{r_0 \eta (r_c/r_0)^{(\eta-1)/\eta}}{t_0} . \quad (5)$$

The time that this event occurred can be found by solving equation (4), and thus the total time for the cloud to dilute the cooled gas in the postshock zone is given by

$$\Delta t = t_0[1 - (r_c/r_0)^{1/\eta}] - \tau(T, v_c, \rho_c) . \quad (6)$$

Substituting equations (2), (5), and (6) into equation (3) gives us

$$\sigma_c = r_0 \eta(\rho_i \rho_c)^{1/2}\left\{\left[1 - \frac{\tau(T, v_c, \rho_c)}{t_0}\right]\left(\frac{r_c}{r_0}\right)^{(\eta-1)/\eta} - \frac{r_c}{r_0}\right\} . \quad (7)$$

We envision that a typical Type II supernova creates a mass M_r of a given element through the r-process and ejects it into the interstellar medium (ISM). If this happens at an average supernova event rate of R_{SN} throughout the lifetime of our galaxy t_{gal}, and the element is thoroughly mixed with the entire galactic mass M_{gal}, an abundance by mass

$$X_r = \frac{M_r R_{SN} t_{gal}}{M_{gal}} \quad (8)$$

will result. The cosmic abundance of this element will also include contributions from the s-process in other sites; hence the total observed abundance equals $X_r + X_s$.

For our observations to show a significant enhancement due to the supernova event, we require the surface density of newly manufactured r-process material

$$\sigma_r = \frac{M_r}{4\pi r_c^2} \quad (9)$$

to increase the surface density of a given element in the swept-up material $(X_r + X_s)(\sigma_i + \sigma_c)$ by a measurable amount. In terms of the fraction $f_r \equiv X_r/(X_r + X_s)$, this means that

$$\sigma_i + \sigma_c \leq f_r \frac{M_{gal}}{4\pi r_c^2 R_{SN} t_{gal}} , \quad (10)$$

to at least double the concentration of a given element over its cosmic abundance.

For the Vela SNR, we must obtain some approximate values for the present radius r_0 and a representative intercloud density ρ_i. One way to accomplish this is to note that a representative upper bound for the temperature of low-density material that has been hit by the blast wave is about $T_b = 10^{6.8}$ K (Kahn et al. 1985). For a Sedov solution with a typical explosion energy of 4×10^{50} ergs, we can evaluate the number density n_i for the propagation of the blast wave,

$$n_i = \left\{\frac{1.5 \times 10^{11}}{[t_0(\mathrm{yr})]^{6/5} T_b}\right\}^{5/2} \quad (11)$$

(Spitzer 1978; eq. 12-26) to obtain $n_i = 0.062$ cm^{-3}, or $\rho_i = 1.5 \times 10^{-25}$ g cm^{-3}. Since this result is proportional to the explosion energy, there is a moderately large uncertainty in ρ_i. Next, we evaluate r_0 according to the relation,

$$r_0 = \frac{0.26[t_0(\mathrm{yr})]^{2/5}}{n_i^{1/5}} \text{ pc} = 19 \text{ pc} \quad (12)$$

(Spitzer 1978; eq. 12-25). This result is independent of the assumed explosion energy. Finally, to obtain a lower bound for ρ_c we note that the current velocity of the blast wave should be about 800 km s^{-1}, and that an approximate upper bound for v_c near the periphery of the remnant is observed to be about 160 km s^{-1} (Jenkins et al. 1984). Through the application of equation (2), we find that $\rho_c = 25\rho_i = 3.8 \times 10^{-24}$ g cm^{-3} (or $n_c = 1.6$ cm^{-3}). This limit for the observed v_c is probably established by the requirement that the cooling time be shorter than a small fraction of t_0, i.e., $\tau(10^4$ K, 160 km s^{-1}, 1.6 cm$^{-3}) = 800$ yr (Hartigan, Raymond, & Hartmann 1987). Higher velocity shocks that occur in clouds of lower density have not yet cooled to the point where they are easily detectable.

The mass fraction of r-process material in the galaxy is estimated from observation to be about $X_r \approx 10^{-7}$, implying a total mass of about $M_r \approx 10^4 M_\odot$ of neutron-rich material in the galaxy. With a supernova rate of, crudely, one per century, and an age for the galaxy of about 10 Gyr, we can infer that each supernova must yield about $10^{-4} M_\odot$ of r-process material (see, for example, Meyer et al. 1992).

For a Galactic baryonic mass of $10^{11} M_\odot$, $t_{gal} = 10^{10}$ yr, $R_{SN} = 0.01$ yr^{-1}, and $r_0 = 19$ pc, we obtain for the term on the right-hand side of equation (10) the quantity

$$\frac{\sigma_r}{X_r + X_s} = 4.6 \times 10^{-5} f_r \left(\frac{r_0}{r_c}\right)^2 \text{ g cm}^{-2} , \quad (13)$$

which represents the amount of an r-process element deposited by the supernova, divided by its respective abundance in the present-day interstellar medium. For comparison, when we insert the parameters we adopted for the Vela remnant into equations (1) and (7) we obtain

$$\sigma_i = 2.9 \times 10^{-6}\left(\frac{r_c}{r_0}\right) \text{ g cm}^{-2} \quad (14)$$

and

$$\sigma_c = 1.8 \times 10^{-5}\left[0.93\left(\frac{r_c}{r_0}\right)^{-3/2} - \frac{r_c}{r_0}\right] \text{ g cm}^{-2} \quad (15)$$

if $\eta = 0.4$. Raising η to 0.6 gives a more favorable (lower) result for σ_c, but then ρ_i must be raised if $r_c/r_0 \ll 1$ because of the importance of cloud evaporation at earlier times in the life of the remnant. For $(r_c/r_0) = 0.2$, 0.4, 0.8, and 0.9, the ratio of $\sigma_r/(X_r + X_s)$ to the sum of σ_i and σ_c is $6.4f_r$, $4.9f_r$, $6.5f_r$, and $9.6f_r$, respectively. Thus, as long as f_r is not less than 0.2, we should see at least a doubling of the abundance of an element throughout most of the nebula. It is important to remember, however, that the validity of this conclusion is very dependent on our having adopted correct values for M_{gal}, t_{gal}, R_{SN} and r_0, all of which have a fair amount of uncertainty. Deviations from spherical symmetry and small-scale clumping of the ejecta may result in some clouds having more, and others less, than the average concentrations.

4. SELECTION OF LIKELY LINES

There are several important conditions that must be met for us to have a reasonable chance to detect r-process elements in the ejecta from a supernova. First, the element must have a large r-process contribution to the sum of its stable isotopes. Second, it must be present in the interstellar medium (or more importantly in the SN ejecta) in the state of ionization which has permitted transitions arising from the ground state to levels of 1 to about 10 eV. Finally, but probably of least importance, it is preferable that the element is not likely to be attached to grains, which would deplete it from the gas phase in which it is visible. We next discuss each of these properties and how each limits the likely elements that might be observed with the *Hubble Space Telescope* or from the ground.

4.1. *r-Process Elements*

The distribution of elements heavier than iron in the solar system shows a number of peaks which may be identified with either slow (s-process) or rapid (r-process) neutron capture

TABLE 1

LINES OBSERVED IN OUR SEARCH FOR r-PROCESS ELEMENTS

λ (Å)	log fλ	Species	Ionization Potential (eV)	Condensation Temperature (K)	f_r[a]
1235.84....	2.36	Kr I	14.00	Very low	0.61
1237.06....	3.04	Ge II	15.93	690	0.46
1239.93....	0.19[b]	Mg II	15.03	1270	
1240.39....	−0.11[b]	Mg II	15.03	1270	
1250.59....	0.83	S II	23.40	700	
1253.81....	1.14	S II	23.40	700	
1259.52....	1.31	S II	23.40	700	
2536.52....	2.93	Hg I	10.43	Very low	0.73
2538.00....	3.38	Os II	17.00	1900	0.96
2538.67....	1.67	Yb II	12.18	...	0.66

[a] Fraction of solar system abundance produced by the r-process (Käppeler et al. 1989).

[b] New f-values by Sofia et al. 1994.

processes. The s-process peaks near Y, Ba, and Pb are due to the small n-capture cross sections associated with closed shells in the relevant nuclei. Peaks centered around Kr, Xe, Eu, and Pt appear to be due to similar abundance maxima in extremely n-rich isotopes (produced in an environment of large n/p ratio) which have β-decayed to stable, and hence observable, isotopes. Elements that are favored by this process are to be found in the intervals of Ge-Rb, Te-Cs, Nd-Lu, and Re-Au (Cameron 1982; Käppeler, Beer, & Wisshak 1989).

Käppeler et al. have used their measured neutron-capture cross sections combined with a general s-process theory to separate the s- and r-process contributions to each of the isotopes of elements heavier than zinc. This yields the solar system's r-process abundances. Of course, the solar system's distribution of r-process elements may not be entirely indicative of our region of the Galaxy, but analyses of extremely metal poor stars whose s-process abundances are so low as to reveal their r-process content show very similar r-process distributions to that of the Sun (Gilroy et al. 1988; Cowan et al. 1995).

4.2. *The State of Ionization*

Throughout most of the interstellar medium starlight succeeds in ionizing most species with an ionization potential, χ_{ion}, less than that of H I, 13.6 eV, or actually somewhat less than that because the convergence of the Lyman lines suppresses the emergent stellar flux near the Lyman limit for photons more energetic than about 13.0 eV. There may be exceptions in dense H I and H_2 clouds, but these regions are irrelevant for supernova remnants. In the Vela remnant many clouds show a higher level of ionization, similar to that in H II regions into which Ly continuum photons may penetrate so that lines from Si III and S III were readily observable with the *Copernicus* satellite (JSW). Hence, we prefer to restrict ourselves to species with χ_{ion} between 13 eV and about 25 eV.

4.3. *Grain Chemistry Considerations*

Many species have been found to be grossly deficient in the interstellar gas because they are attached to the grains (Jenkins 1987). The propensity to stick on grains correlates very closely with the condensation temperature of the element, though other factors are also involved (Cardelli 1994; York 1994). However, in the Vela remnant JSW showed that species usually depleted from the general interstellar gas are not depleted, presumably due to shock heating and grain evaporation, so we consider the affinity to grains to be less important than it would be in undisturbed gas. In fact, depletion onto grains may reduce the concentration of certain species in the ambient gas but not in the supernova ejecta.

TABLE 2

TARGET STARS

Star (HD)	Spectral Type	Distance (pc)	Separation from Pulsar	Mean S/N of Data
72127 A......	B3 III	710	1°06	180
72127 B......	B3 V	710	1.06	50
72350	B5 IV	400	0.91	50
72798	B5 III	580	0.71	70
74455	B1.5 V	420	3.14	250

4.4. *Permitted Transitions*

Since excited levels are never substantially populated in interstellar clouds, we can observe only elements with permitted transitions originating from the ground state and terminating in states between 1 and 10 eV excitation, thereby providing lines between 1200 and 12,000 Å and accessible to *HST* or ground-based observatories. Such lines can be recognized by searching the compilations of Atomic Energy Levels and other publications of the National Bureau of Standards (now NIST). For lines without published transition probabilities one can select those that do not violate any selection rules and hence are likely to have A-values near 10^8 s^{-1}. If the line, or a restrictive upper limit is found, an accurate A-value can usually be measured in the laboratory.

With those factors in mind, we have used the GHRS to search for absorption lines of Ge II, Kr I, and Os II in the interstellar gas of the Vela remnant. Both Ge and Kr have many stable isotopes exposed to β-decay of neutron-rich isotopes of iron peak elements, thereby optimizing the chance of finding an excess abundance. Krypton is a noble gas, ensuring that it will not be locked on grains as are many other elements. Osmium is representative of the most massive stable r-process peak just below lead. In the same spectral regions as the Os II line are also lines of Yb II and Hg I, both of which have substantial r-process contributions. The wavelengths and f-values of the lines we selected are listed in Table 1, along with the ionization potentials, condensation temperatures, and f_r of the species they represent. We include data for the two Mg II lines and three S II lines that we have used for comparison purposes.

5. OBSERVATIONS

Four B stars were selected by their relatively small angular distance from Vela pulsar to diminish the dilution factor of the expanding supernova ejecta. They were observed both in the Ge II–Kr I and Os II spectral regions. Data in the Ge II–Kr I region for one star observed for another program is included in our survey. The stars are described briefly in Table 2, where we also show the signal-to-noise (S/N) for each observation.

The first seven lines of Table 1 were observed with the small science aperture[3] and grating G160M in the GHRS, yielding a resolution of about 20,000. The Os II region was observed with

[3] For HD 74455 we used the large science aperture to maximize the S/N.

TABLE 3

EQUIVALENT WIDTHS OF INTERSTELLAR LINES ($-\log W/\lambda$)

		Star (HD)				
Species	λ	72127A	72127B	72350	72798	74455
Kr I	1235	>5.79	>5.68	>5.79	...	>6.40
Ge II	1237	5.49	>5.68	5.27	...	5.47
Mg II......	1239	4.92	4.98	4.95	...	5.00
Mg II......	1240	5.16	5.19	4.89	...	5.41
S II	1250	4.05	4.08	3.92	...	4.00[a]
S II	1253	3.85	3.85	3.83	...	3.82[a]
S II	1259	3.78	3.79	3.80	...	
Hg I	2536	>6.50	...	>6.04	>6.32	
Os II	2538	>6.50	...	>6.04	>6.32	
Yb II	2538	>6.50	...	>6.04	>6.32	

[a] From JSW.

echelle B and the small science aperture, providing a resolution of about 70,000. All observations were made in the FP-split mode to facilitate the elimination of fixed pattern noise, the analysis of which was accomplished by a special program written by one of us (E. B. J.). To compensate for the limited resolution in the 1235 Å region we obtained high S/N as shown in Table 2.

After combining separate exposures and minimizing their fixed pattern noise, we determined the equivalent widths (or their upper limits) and radial velocities, as sumarized in Table 3, using the MSLAP analysis program[4] which operates in IDL. While the primary purpose of this study was to obtain column densities, we note here that the Ge II lines and Mg II lines always agreed to within 2 km s^{-1}, which is close to the uncertainty of each radial velocity measurement. Upper limits to equivalent widths were established by measuring the strongest "feature" within 1 Å of the expected wavelength and calling it an upper limit. Even if such a feature appears to be a 3 σ detection, the discrepancy of its radial velocity, as compared with readily identifiable interstellar lines, excludes the possibility that we have detected the line for which we were searching. Column densities or their upper limits are shown in Table 4. Upper limits are approximately 3 σ limits.

Except for S II, all of the relevant lines lie on or very close to the linear section of the curve of growth. Hence, for converting their equivalent widths to column densities there was no need to estabish the velocity dispersion b, and thus column densities, or their upper limits, are simply proportional to the equivalent widths of the lines. For S II, which serves very well as a comparison species because it is hardly depleted from the interstellar gas, the lines are substantially saturated. The S II column densities for HD 74455 and HD 72127A are taken from JSW and Wallerstein, Silk, & Jenkins (1980) from *Copernicus* data where their uncertaintieis are ± 0.2 and 0.15 dex, respectively. For both HD 72127B and HD 72350 we estimate the velocity parameter b to be 15 km s^{-1}. Due to the nonlinearity of the curve of growth, an error of 5 km s^{-1} reduces the column density by only 0.2 dex if $b = 20$ but permits an increase of 0.8 dex if $b = 10$ km s^{-1}. Hence, the uncertainties in column density ratios are dominated by the uncertainty in b for S II. The data for four comparison stars not associated with supernovae have been summarized by Cardelli (1994, see also Hobbs et al. 1993). Their uncertainties are about ± 0.2 dex except for the large uncertainties in S II due to strong saturation (van Steenburg & Shull 1988). Given the fact that uncertainties in b will not greatly reduce the column density of S II thereby leading to an excess of, e.g., Ge II/S II, the conclusions of this paper are not as sensitive as would be the case if they would be upset by a larger column density of S II.

Using the theoretical concepts developed in § 3, we can predict the column densities of r-process species contributed by the Vela supernova assuming a distance of 300 parsecs (Ögelmann, Koch-Miramond, & Auriere 1989; Sahu 1992; Jenkins & Wallerstein 1995). We took r-process production ratios as estimated by Käppeler, Beer, & Wisshak (1989) from their relative abundances given in the last column of their Table 4. For gas near zero velocity we must still take into account the dilution due to material in the line of sight not associated with the supernova. We can estimate this background from the observed sulfur column density and the cosmic ratio of S to each species. Using a mean S column density of 3×10^{15} cm^{-2}, we show these in the last column of Table 5.

A comparison of our results in Table 4 with the predictions shown in the last column of Table 5 shows that our Ge detection and upper limits for the other species fall well within the expected background provided by foreground interstellar matter. For possible components at displaced velocities our upper limits for Ge II are 11.3 dex for the first three stars in Table 4 and 10.6 dex for HD 74455, which is significantly below the prediction for $r_c/r_0 = 0.2$ shown in Table 5.

[4] MSLAP is a third-generation program developed for NASA. MSLAP is copyrighted by Charles L. Joseph and Edward B. Jenkins.

TABLE 4

COLUMN DENSITIES OF INTERSTELLAR LINES IN THE VELA REMNANT

	log Column Density (cm^{-2})					Mean of Three Stars[a] Outside Vela	
Species	HD 72127A	HD 72127B	HD 72350	HD 72798	HD 74455		ζ Oph[b]
Mg II......	14.95	14.9	15.1	14.85	...	...	14.45
S II	15.45	15.45	15.6	...	15.6	15.5[c]	15.5[c]
Ge II	11.55	<11.3	11.75	...	11.5	11.4	11.35
Kr I	<11.9	<12.0	<11.9	...	<11.3	<11.2	11.5
Yb II	<11.9	...	<12.35	<11.95			
Os II	<10.2	...	<10.65	<10.25			
Hg I	<10.65	...	<11.1	<10.7			

[a] From Hobbs et al. 1993.

[b] From Cardelli, Savage, & Ebbets 1991 and Savage, Cardelli, & Sofia 1992.

[c] Set arbitrarily to be equal to the mean of the S II column density of the Vela stars.

TABLE 5

PREDICTED r-PROCESS COLUMN DENSITIES FOR TWO RATIOS OF CLOUD DISTANCE TO TOTAL RADIUS OF THE REMNANT

	$r_c/r_0 = 0.2$		$r_c/r_0 = 0.9$		
ELEMENT	log Enrichment	log N	log Enrichment	log N	BACKGROUND[a] log N
Ge II......	0.60	12.0	0.73	10.7	11.9
Kr I	0.69	11.7	0.83	10.4	11.5
Yb II......	0.72	9.5	0.87	8.2	9.6[b]
Os II	0.85	10.1	1.00	8.8	9.3[b]
Hg I	0.75	9.6	0.90	8.3	9.3

[a] Asuming log N(S II) = 15.5 cm^{-2} as observed for the Vela stars, and that the abundance ratios are the cosmic values (Anders & Grevesse 1989).

[b] The background may be less due to depletion onto grains.

As shown in Table 1, several species, especially Ge, are expected to have a substantial *s*-process contribution. During evolution to the collapse stage there is good reason to expect an enhancement of *s*-process nuclei at some level within the star. The enhanced *s*-process layer may then be lost by a stellar wind and later swept up by the explosion or be lifted off without further nuclear processing by the explosion. In either case, an enhancement of *s*-process species might be expected. We have not searched for specific *s*-process elements, but Ge in the solar system is 54% *s*-process. It was detected in three of four Vela stars slightly above the level of the four comparison stars in Table 4 but below the calculated background shown in Table 5. We are not aware of any substantial effort to detect *s*-process species in the Vela remnant.

6. INTERPRETATION

The ratios of column densities in Table 4 are not abundance ratios until we have taken both ionization and depletion onto grains into account. Except for Hg I and Yb II, all the observed species have ionization potentials above 13.5 eV and hence are likely to be representative of the total abundance. Except for S, we know of no observations of interstellar column densities for the next higher state of ionization above the one we have observed. Lines of S III were observable with *Copernicus*, and ratios of S III/S II are available in the literature. In HD 74455, JSW found log N(S III) − log N(S II) = −0.13 in the low-velocity cloud. In the same cloud they found somewhat higher ionization for iron with log N(Fe III) − log N(Fe II) = +0.06 while for silicon they found log N(Si III) − log N(Si II) = +0.45 but with an uncertainty of +0.4, −0.6 for the Si III column density due to saturation. It appears that second ionization may double the total column densities for these elements in the Vela environment. The doubly ionized species may be due to the line of sight passing through an H II region or to the peculiar conditions in the shocked clouds (including the low-velocity gas) in Vela (see § IV of JSW). In ζ Oph Morton (1975) found that the singly ionized species exceed the doubly ionized form by about a factor of 10. It appears that ionization should not grossly distort the column density ratios of Table 4 except possibly for Hg and Yb which we did not detect anyhow, and were not primarily target species.

Depletion of interstellar gases onto the grains can significantly alter the relative abundances in the gas phase. Even though the physical conditions in the Vela clouds show reduced depletions (JSW), the possibility that the column density ratios do not represent abundance ratios must be considered. Interstellar depletions are known to correlate with the condensation temperature of the species, so we have included condensation temperatures in Table 1. Sulfur is known to be minimally depleted, if at all, so we expect that Kr and Hg will be undepleted and that Ge will be no more depleted than S. If the new *f*-values of Sofia, Cardelli, & Savage (1994) are correct, Mg is depleted in most interstellar gas and appears to be depleted in the Vela clouds by nearly a factor of 10 relative to the solar ratio of Mg to S. This is a bit surprising considering the low level of depletion of other elements in HD 74455 (JSW), but the Mg depletion varies by as much as 1.0 dex at a given value of E_{B-V} (Murray et al. 1984).

The very high condensation temperature of Os means that it is likely to be attached to the grains in the outer envelopes of cool stars and to remain so after ejection into the interstellar medium. However, Os ejected by a supernova will probably be in gaseous form and is not likely to become attached to grains except perhaps after it has become part of a high density molecular cloud. Hence, any detection of Os would be indicative of recent supernova injection, though its absence may be due to depletion.

7. CONCLUSIONS

Table 4 shows that we have not detected an excess of any of the *r*-process elements investigated. Wallerstein & Gilroy (1992) also failed to detect an excess of Eu II, Gd II, or other *r*-process species in the optical region of several Vela stars. The low second ionization potentials of those species may have been a factor.

A comparison of Tables 4 and 5 show that for the first four stars, all of which are about 1° from the pulsar, our Kr and Os upper limits fall only slightly above the predicted log N values for inner regions of the remnant. With higher S/N or by a survey of additional stars to take advantage of likely fluctuations in the density of the ejecta and intervening clouds, there is a good chance for a positive detection of both species. Yb II and Hg I are not likely detections, but they were included only because their resonance lines are close to the Os II line. Our Ge II data fall below expectations perhaps because it is depleted onto grains while S II, on which our background is based, is not depleted.

We might ask if the absence of a detection argues against the *r*-process having an origin in neutrino-heated ejecta. The answer is "no." If the hot bubble *r*-process picture is right, then we expect only about 10^{-4} $M_{\odot}$ of *r*-process material per supernova. In fact, if we had seen vast amounts of r-process material (if we had seen anything it might indicate "vast" amounts), then that would strongly argue *against* the hot bubble picture. It might instead support an r-process from decompressed core material shot out by convection/rotation, where one might find as much as 0.1 $M_{\odot}$ of r-processed matter.

It appears that we may have come close to detecting r-process ejecta from the Vela supernova. With the improved optics and a resumption of the operation of echelle A on *HST* there is a good chance that a survey of many stars behind the remnant will achieve a positive detection and perhaps even the ratio of Os/Kr, which will shed light on the physics of supernovae.

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REFERENCES

Anders, E., and Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Aschenbach, B. 1993, in UV and X-Ray Spectroscopy of Astrophysical and Laboratory Plasmas, ed. E. H. Silver & S. M. Kahn (Cambridge: Cambridge Univ. Press), 434
Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, Rev. Mod. Phys., 29, 694
Cameron, A. G. W. 1957, PASP, 69, 201
———. 1982, Ap&SS, 82, 123
Cardelli, J. A. 1994, Science, 265, 209
Cardelli, J. A., Savage, B. D., & Ebbets, D. C. 1991, ApJ, 383, L23
Cowan, J. J., Burris, D. L., Sneden, C., McWilliam, A., & Preston, G. W. 1995, ApJ, 439, L51
Cowan, J. J., Thielemann, F. K., & Truran, J. W. 1991, Phys. Rep., 208, 267
Gilroy, K. K., Sneden, C., Pilachowski, C. H., & Cowan, J. J. 1988, ApJ, 327, 298
Hartigan, P., Raymond, J., & Hartmann, L. 1987, ApJ, 316, 323
Hobbs, L. M., Welty, D. E., Morton, D. C., Spitzer, L., & York, D. G. 1993, ApJ, 411, 750
Jenkins, E. B. 1987, in Interstellar Processes, ed. D. J. Hollenbach & H. A. Thronson, Jr. (Dordrecht: Reidel), 533
Jenkins, E. B., Silk, J., & Wallerstein, G. 1976, ApJS, 32, 681 (JSW)
Jenkins, E. B., & Wallerstein, G. 1995, ApJ, 440, 227
Jenkins, E. B., Wallerstein, G., & Silk, J. 1984, ApJ, 278, 649
Kahn, S. M., Gorenstein, P., Harnden, F. R., & Seward, F. D. 1985, ApJ, 229, 821
Käppeler, F., Beer, H., & Wisshak, K. 1989, Rep. Prog. Phys., 52, 945
Mathews, G. J., Bazan, G., & Cowan, J. J. 1992, ApJ, 391, 719
McKee, C. F., & Cowie, L. L. 1975, ApJ, 195, 715
McKee, C. F., & Ostriker, J. P. 1977, ApJ, 218, 148
Melotte, P. J. 1926, MNRAS, 86, 636
Meyer, B. S. 1994, ARA&A, 32, 153
Meyer, B. S., Mathews, G. J., Howard, W. M., Woolsey, S. E., & Hoffman, R. D. 1992, ApJ, 399, 656
Morton, D. C. 1975, ApJ, 197, 85
Murray, M. J., Dufton, P. L., Hibbert, A., & York, D. C. 1984, ApJ, 282, 418
Ögelmann, H., Koch-Miramond, L., & Auriere, M. 1989, ApJ, 342, L83
Qian, Y.-Z., Fuller, G. M., Mayle, R. L., Mathews, G. J., Wilson, J. R., & Woosley, S. E. 1993, Phys. Rev. Lett., 71, 1965
Rishbeth, H. 1958, Australian J. Phys., 11, 550
Sahu, M. S. 1992, Ph.D. thesis, Univ. of Groningen, p. 132
Savage, B. D., Cardelli, J. A., & Sofia, U. J. 1992, ApJ, 401, 706
Sedov, L. 1969, Similarity and Dimensional Methods in Mechanics (New York: Academic)
Sofia, U. J., Cardelli, J. A., & Savage, B. D. 1994, ApJ, 430, 650
Spitzer, L., Jr. 1978, Physical Processes in the Interstellar Medium (New York: Wiley)
Taylor, J. H., Manchester, R. H., & Lyne, A. G. 1993, ApJS, 88, 529
Thompson, A., O'Sullivan, D., Wenzel, K.-P., Bosch, J., Keegan, R., Domingo, C., & Jansen, F. 1993, in Proc. 23rd Internat. Cosmic Ray Conf., Calgary, 1, 603
van Steenburg, M. E., & Shull, J. M. 1988, ApJ, 330, 942
Wallerstein, G., & Gilroy, K. K. 1992, AJ, 103, 1346
Wallerstein, G., Silk, J., & Jenkins, E. B. 1980, ApJ, 240, 834
Witti, J. 1993, in Proc. 7th Workshop on Nuclear Astrophysics, Ringsberg Castle, Tegernsee, Germany, ed. W. Hillebrandt & E. Müller (Garching: MPI), 107
Woosley, S. E., & Hoffman, R. D. 1992, ApJ, 395, 202
Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, ApJ, 433, 229
Wu, C-C., Crenshaw, D. M., Fesen, R. A., Hamilton, A. J. S., & Sarazin, C. L. 1993, ApJ, 416, 247
York, D. G. 1994, Science, 265, 191