THE ASTROPHYSICAL JOURNAL, 233:154–162, 1979 October 1

ABUNDANCE INHOMOGENEITIES IN THE CASSIOPEIA A SUPERNOVA REMNANT

ROGER A. CHEVALIER
Kitt Peak National Observatory
AND
ROBERT P. KIRSHNER[1]
Department of Astronomy, University of Michigan
Received 1979 March 22; accepted 1979 April 9

ABSTRACT

Quantitative spectral information has been obtained for several of the fast-moving knots in Cas A. We find that the strengths of lines of [S II], [Ar III], and [Ca II] are correlated with each other and that this group of lines can vary by large factors relative to lines of oxygen. Sulphur, argon, and calcium are the products of oxygen burning, so a simple interpretation of our result is that different parts of the remnant come from portions of a stellar interior that have undergone different amounts of oxygen burning. The abundance ratios are uncorrelated with the kinematic properties of the knots. We have examined Minkowski's spectra of Cas A and have confirmed that neon is present in one of the fast knots, although the location of the knot is not known.

Subject headings: nebulae: abundances — nebulae: individual — nebulae: supernova remnants

I. INTRODUCTION

Cassiopeia A was initially discovered as a radio source; optical identification was subsequently made by Baade and Minkowski (1954), who found two kinds of optical nebulosity with different space motions —the fast-moving knots and the quasi-stationary flocculi (QSFs). From the proper motions of the fast knots, it is possible to deduce the age of Cas A. Kamper and van den Bergh (1976*b*) estimate that the explosion occurred in 1657. A supernova event was not observed at that time.

The fast-moving knots in Cas A are of special interest because they appear to be overabundant in the products of advanced stages of nucleosynthesis (Peimbert and van den Bergh 1971; Peimbert 1971; Chevalier and Kirshner 1978, hereafter Paper II). The observations of Kirshner and Chevalier (1977, hereafter Paper I) indicate that hydrogen makes up a very small mass fraction of the knot material (Paper II). The evidence is good that the envelope of the star was removed prior to the explosion that ejected the fast-moving knots. In Paper II, the abundances in the knots were derived by comparing observed line strengths with those of shock models by Raymond (1979). We compared the abundances to those calculated from the evolution of massive stellar cores. For purposes of the comparison, we assumed that the stellar core material was completely mixed. The agreement of the observations with theory was not very satisfactory because of the low observed values of the C, Ne, and Mg abundances. It was suggested that the Cas A progenitor was very massive, because this appeared to give the best fit. However, another possibility was that complete mixing did not occur, so that the comparison was not valid.

Observations of Cas A have shown that there are large variations in the [S II] λλ6716–6731/[O III] λ5007 ratio over the face of the remnant (Paper I; Kamper and van den Bergh 1976*a*, *b*). However, it has not been possible to deduce a S/O abundance ratio directly from these observations because the [S II] λλ6716–6731 lines are subject to collisional deexcitation and are thus quite sensitive to density, while the strength of the [O III] λ5007 line may be sensitive to the degree of shock excitation. We have now obtained spectrophotometry in five regions in Cas A, including some where the apparent [S II]/[O III] line ratio was known to take on extreme values. We have found strong evidence for real chemical inhomogeneities.

In § II we present the new observations. In § III, the abundances in the brightest part of Cas A, filament 1, are rediscussed in light of the new observations. The results on abundance inhomogeneities are presented in §§ IV and V, and are discussed in § VI.

II. OBSERVATIONS

New quantitative spectral information was obtained on five of the fast knots in Cas A. Filament 1 (Baade and Minkowski 1954; Peimbert and van den Bergh 1971; Searle 1971) was observed in the blue in order to set better limits on emission lines in this region. KB 33 and KB 61 (KB refers to a knot listed by Kamper and van den Bergh 1976*b*) were chosen because they were known to be strong [S II] λλ6716–6731 emitters. In choosing these knots, the color

[1] Guest Observer, Kitt Peak National Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1

OBJECTS OBSERVED IN CASSIOPEIA A

Object	Position[a] X	Position[a] Y	Wavelength Range (Å)	1978 UT Date	Integration Time (s)
[O III]	+64″3	+ 8″7	4000–7500	August 29	4400
			3500–7000	August 30	1600
KB 33	−25.8	+ 77.7	4000–7500	August 29	6000
			3500–7000	August 30	4000
Filament 1	+63.5	+ 64.8	3500–7000	August 30	8000
KB 61	−22.4	+ 87.8	4000–7500	August 31	4400
KB 115	+176.9	+ 56.7	4000–7500	September 1	8400
Diffuse	+51.0	− 41.0	4000–7500	August 29	400
QSF 3	+7.8	+ 47.2	3500–7000	August 30	2400
Bell 38	−43.2	− 149.0	4000–7500	August 29	4400

[a] Relative to the remnant's center of expansion at $\alpha = 23^h21^m12^s$, $\delta = +58°32'24''$ (1950.0).

photograph of Cas A by Kamper and van den Bergh (1976*a*) was helpful. The [O III] filament was also chosen by reference to this photograph. Finally, we observed KB 115 because it is far from the center of expansion and has a high proper motion (Kamper and van den Bergh 1976*b*). It is near the tip of the Cas A "jet" feature.

A journal of the observations is given in Table 1. The scans were obtained with the Intensified Image Dissector Scanner (IIDS) at the Cassegrain focus of the Mayall 4 m telescope on Kitt Peak. The entrance aperture used for all the scans was 5″3, and the effective resolution of the spectra was 20 Å. Simultaneous sky measurements were obtained through a second

TABLE 2

LINE STRENGTHS IN CASSIOPEIA A

Line	[O III] F	[O III] I	KB 33 F	KB 33 I	Filament 1 F	Filament 1 I	KB 61 F	KB 61 I	KB 115 F	KB 115 I
[O II] λ3727	7.5	42.0	:9	:51	4.15	23.0	...	...	...	...
[Ne III] λ3869	< 7.0	< 33.0	< 9	< 42	< 0.08	< 0.4	...	...	...	...
Ca II λ3933	< 7.0	< 33.0	< 9	< 42	< 0.08	< 0.4	...	...	...	...
[Ne III] λ3968	< 7.0	< 29.0	< 9	< 37	< 0.08	< 0.3	...	...	...	...
[S II] λ4070	< 1.3	< 5.0	13	50	2.58	9.7	< 1.0	< 4.0	< 14	< 55
Ca I λ4226	< 1.3	< 5.0	< 13	< 35	< 0.08	< 0.3	< 1.0	< 3.0	< 14	< 40
[O III] λ4363	< 1.3	< 4.0	< 13	< 35	1.07	2.9	0.8	:2.0	< 14	< 38
Mg I λ4571	< 1.3	< 2.0	< 13	< 25	< 0.08	< 0.2	< 0.8	< 2.0	< 14	< 26
[Fe III] λ4658	< 1.3	< 2.0	< 13	< 21	< 0.08	< 0.2	< 0.8	< 2.0	< 14	< 23
[Ar IV] λ4711	< 1.3	< 2.0	< 13	< 20	0.17	0.26	< 0.8	< 2.0	< 14	< 21
[Ar IV] λ4740	< 1.3	< 2.0	< 13	< 20	0.17	0.26	< 0.8	< 2.0	< 14	< 21
Hβ λ4861	< 1.3	< 1.0	< 13	< 16	< 0.1	< 0.12	< 0.8	< 1.0	< 14	< 17
[O III] λ4959	22.0	23.0	20	21	22.0	23.0	24.0	25.0	}100	100
[O III] λ5007	78.0	77.0	80	79	78.0	77.0	76.0	75.0		
[Ar III] λ5192	< 1.3	< 1.0	< 15	< 12	< 0.13	< 0.1	< 1.0	< 0.8	< 10	< 8
[N I] λ5198	< 1.3	< 1.0	< 15	< 12	< 0.13	< 0.1	< 1.0	< 0.8	< 10	< 8
[O I] λ5577	< 1.3	< 1.0	< 15	< 12	< 0.13	< 0.1	< 1.0	< 0.8	< 9	< 5
[O I] λ6300	11.0	3.0	46	13	}27.0	7.8	{23.0	6.7	194	56
[O I] λ6364	5.0	1.5	15	4			5.0	1.5	77	22
[Ar V] λ6435	< 1.5	< 0.3	< 15	< 3	< 0.15	< 0.03	< 0.6	< 0.15	< 10	< 6
[N II] λ6548	< 1.5	< 0.3	< 15	< 3	< 0.15	< 0.03	< 0.6	< 0.15	< 10	< 5
Hα λ6562	< 1.5	< 0.3	< 15	< 3	< 0.15	< 0.03	< 0.6	< 0.15	< 10	< 5
[N II] λ6584	< 1.5	< 0.3	< 15	< 3	< 0.15	< 0.03	< 0.6	< 0.15	< 10	< 5
[S II] λ6724	< 1.8	< 0.3	817	147	49.8	9.0	97.5	18.0	729	131
[Ar V] λ7006	< 2.0	< 0.3	< 15	< 3	...	...	< 1.0	< 0.2	< 15	< 2
[Ar III] λ7136	< 2.0	< 0.3	120	16	...	...	14.8	1.9	78	10
[Ca II] λ7291	< 2.0	< 0.3	132	16	...	...	2.3	0.3	< 29	< 4
[O II] λ7325 [Ca II] λ7324	}107.0	13.0	132	16	...	...	81.0	10.0	526	63
[O III] flux[a]	5.4×10^{-15}		7.6×10^{-16}		9.55×10^{-14}		1.6×10^{-14}		6.9×10^{-16}	
Velocity	+2070 ± 100		+1420 ± 50		+260 ± 40		−2308 ± 70		−2823 ± 40	

[a] Ergs cm^{-2} s^{-1} through 5″3 aperture.

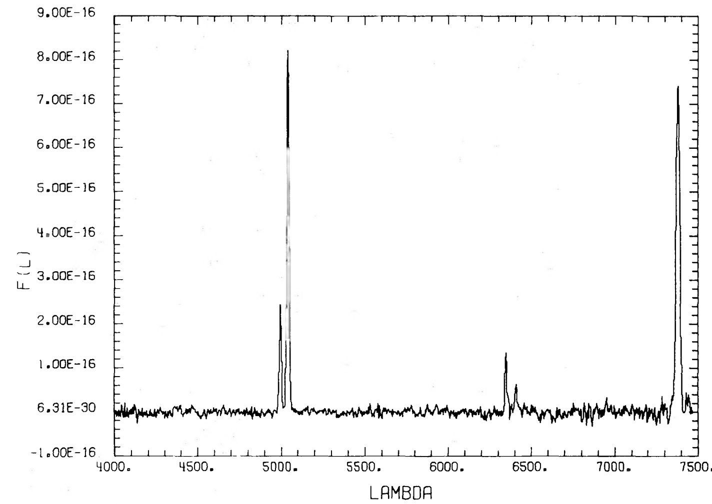

FIG. 1.—Plot of flux density (in ergs cm^{-2} s^{-1} $Å^{-1}$) versus wavelength (in Å) for the [O III] filament. The only lines present are [O III] λλ4959, 5007, [O I] λλ6300, 6364, and [O II] λλ7320, 7320. The [O II] lines are blended.

aperture, located 52″ away. Although the apertures were generally aligned east-west, in some cases the spectrograph was rotated so that the sky measurements were not contaminated by bright stars or by emission knots. Measurements of the object and of the sky were made through each aperture, and subtracted. The results were reduced to fluxes using measurements of standard stars and the KPNO reduction program.

To convert the observed fluxes F to the emitted ones I, we have adopted Searle's (1971) determination of the absorption: $A_v = 4.3$ mag. We have then used the form of Whitford's (1958) relation given by Miller and Mathews (1972) to derive the line ratios at the source. We have adopted Searle's system, setting the sum of the [O III] doublet λλ5007, 4959 to 100, as detailed in Table 2. Table 2 also shows the flux observed at Earth from the doublet in ergs cm^{-2} s^{-1} and the measured radial velocity. Two of the reduced scans are illustrated in Figure 1 (the [O III] filament) and in Figure 2 (KB 33).

In addition to the measurements of fast-moving knots, we made brief observations of three other regions that are worth mentioning. We measured a radial velocity for the low surface brightness region listed in Table 1 as the [S II] region. This is a conspicuous feature in van den Bergh's color plate, but not one for which a proper motion is available because it is so diffuse. We find two velocity components in a single 5″ aperture at -4080 ± 75 km s^{-1} and -1850 ± 75 km s^{-1}. Space motions, calculated as

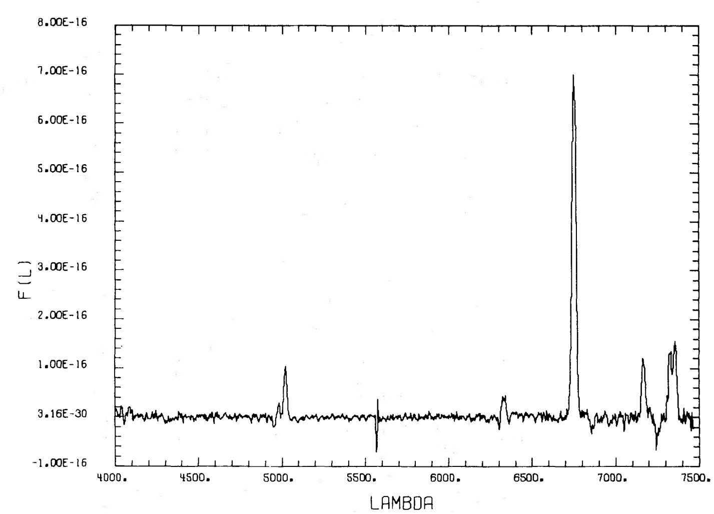

FIG. 2.—Plot of flux density (in ergs cm^{-2} s^{-1} $Å^{-1}$) versus wavelength (in Å) for knot 33 of Kamper and van den Bergh (1976*b*). The lines present are [O III] λλ4959, 5007, [O I] λ6300, [S II] λλ6716, 6731, [Ar III] λ7136, [Ca II] λ7291, and [O II] λλ7320, 7330; note that the [Ca II] line is somewhat blended with the red [O II] lines. The great strength of the [S II] emission relative to the [O III] emission is evident. The feature at λ5577 is due to inaccurate subtraction of a night-sky line. The "absorption" features (e.g., at λ7230) indicates that there was some emission in the sky aperture; this emission has a large redshift.

described for the [O III] knot in § IV, are 4950 km s^{-1} and 3350 km s^{-1}.

The second feature we observed is QSF 3 (Kamper and van den Bergh 1976*b*), which we found had a radial velocity of -120 ± 50 km s^{-1}, in agreement with KB's value of -163.

A third feature is the optical knot associated with the radio feature discovered by Bell (1977). In his high-resolution map of Cas A, Bell noted that just one radio knot (38 in his list) was coincident with an optical feature that van den Bergh first noted in 1967. Since then, the optical knot has brightened and changed its internal structure, but has not moved. The radio object is the most compact feature in Cas A and is located outside the general shell of radio emission. We obtained a spectrum of the optical feature, which shows strong emission lines of [N II] and Hα along with weak [O I], just as is seen in QSFs (Paper I).

The radial velocity is $v = -300 \pm 50$ km s^{-1}, which is comparable to velocities measured in other QSFs (Kamper and van den Bergh 1976*b*). If the radio knot and the optical knot have a physical connection, then we must conclude that the QSFs play a role in the structure of the radio source.

III. FILAMENT 1

In Table 3 the line intensities determined here for filament 1 are compared with those used in Paper II. It can be seen that our results compare quite well with those of Searle (1971); the only significant discrepancy is with the [O I] λλ6300–6364 lines. The mean ratio of our results divided by Searle's (including five measures) is 1.16 ± 0.26. Searle estimated that the accuracy of his results was $\pm 25\%$. The sensitivity of the new observations is about a factor of 10 better than that of Searle's.

The line intensities also compare quite well with the intensities in knot 2F4 (Paper I). It was noted in Paper II that the spectra of filament 1 and knot 2F4 are very similar, and the interpretation was carried out for the combined data on the two knots. We have now detected [Ar IV] λ4711 and λ4740 in filament 1 at a level very close to that observed in 2F4.

The discrepancy between the new observations of filament 1 and the observations of 2F4 concerns the weak lines. We have set upper limits on the lines [Ar III] λ5192, [O I] λ5577, and [Ar V] λ6435 which are lower than their estimated strengths in 2F4. However, the data on 2F4 were photographic, and it is likely that we overestimated the strengths of the weak lines (Paper I). Evidence that this was the case came from the fact that the temperatures derived from the auroral lines of [Ar III] and [O I] were higher than expected (Paper II). Using the new observations of filament 1, we can set an upper limit to the [O I] temperature of 12,000 K. This is lower than the temperature derived

TABLE 3

LINE STRENGTHS IN FILAMENT 1 FOR $A_V = 4.3$

Line	Searle	IIDS	Paper I	Model C
[O II] λ3727	17.5	23	...	304
[Ne III] λ3869	< 6	< 0.4	...	3.9
Ca II λλ3933, 3968	< 6	< 0.4	...	3.4
[Ne III] λ3968	< 5	< 0.3	...	1.2
[S II] λλ4069–4076	9.0	9.7	...	3.0
Ca I λ4226	< 4	< 0.3	...	0.8
[O III] λ4363	3.6	2.9	...	4.1
Mg I λ4571	< 2	< 0.2	...	1.4
[Fe III] λ4658	< 2	< 0.2	...	10.0
[Ar IV] λ4711	< 2	0.26	} 0.44	...
[Ar IV] λ4740	< 2	0.26		
Hβ λ4861	< 2	< 0.12	< 0.10	24.0
[O III] λ4959	} 100.0	23.0	} 100.0	100.0
[O III] λ5007		77.0		
[Ar III] λ5192	< 1	< 0.1	0.19	...
[N I] λ5198	< 1	< 0.1	< 0.06	1.14
[O I] λ5577	< 1	< 0.1	0.16	...
[N II] λ5755	< 1	< 0.1	< 0.06	1.7
[O I] λ6300	} 5.2	7.8	3.6	} 4.4
[O I] λ6364			1.4	
[Ar V] λ6435	< 0.3	< 0.03	0.05	...
[N II] λ6548	< 0.3	< 0.03	< 0.01	15.0
Hα	< 0.3	< 0.03	< 0.01	77.0
[N II] λ6584	< 0.3	< 0.03	< 0.01	45.0
[S II] λλ6717–31	8.3	9.0	6.5	32.0
[Ar V] λ7006	< 0.2	...	0.18	...
[Ar III] λ7136	1.7	...	2.8	...
[Ca II] λ7291	< 0.2	...	0.14	0.54
[O II] λλ7320–7330	} 8.5	...	7.4	10.4
[Ca II] λ7324				
[Ar III] λ7751	0.65	...	...	...
[S III] λ9069	5.0	...	...	...
[S III] λ9532	11.5	...	...	...
[S II] λ10300	7.8	...	...	...

from the [O III] lines (Searle 1971) and is thus in accord with expectations for a line of lower ionization.

Our observations of filament 1 show that the intensities of the [Ar IV] λ4711 and [Ar IV] λ4740 lines are about equal. This is a density-sensitive ratio (Saraph and Seaton 1970) and in the low density limit $I(\lambda 4740)/I(\lambda 4711) \approx 0.7$. Our observations are consistent with the low-density limit, so that we can only set an upper limit on the density $n_e \gtrsim 10^4 T_4^{1/2}$ cm^{-3}, where T_4 is the temperature of the emitting region in units of 10^4 K.

The observations of filament 1 can be used to set upper limits on element abundances using the same technique that was described in Paper II. Once again Raymond's (1979) model C is used in the interpretation. Of particular interest are the [Ne III] λ3869 and λ3968 lines. Minkowski (1957) claimed to have observed a line of [Ne III] in Cas A, and in Paper II it was assumed that he observed the line in filament 1, the brightest of the fast knots. An estimate of the line strength was obtained on the basis of the fact that Minkowski did not report observing the [Ar IV] lines. We have had the opportunity to examine Minkowski's spectra of Cas A and have found that he did not detect [Ne III] in filament 1, but in another fast knot which he called filament 5 (see § V). His deepest plate of filament 1 is the spectrum N194 taken on 1953 October 14. While the lines of [O II] λλ3726–3729 and [S II] λλ4069–4076 are clearly present, the [Ne III] λ3869 line is absent. From our observations, it is possible to set an upper limit on the Ne/O ratio in filament 1. Using the same techniques as in Paper II, we find that Ne/O by mass is less than 0.016.

The observed wavelength region includes the [Fe III] λ4658 line, for which there is sufficient atomic data to predict its intensity (Raymond 1979). Comparing the observed upper limit with that in Raymond's model C yields Fe/O (by mass) < 0.004. This can be compared with the result given in Paper II that Fe/O < 0.01, based on the assumption that the line observed near λ7376 is a permitted Fe II line. Actually, that was probably a misidentification. Lines at 7377.9 Å and 7411.6 Å have been observed in the Orion nebula (Grandi 1975), and they can be identified as the two strongest members of the $a\,^2D$–$a\,^2F$ multiplet of Ni II (Garstang 1968). Given the [Ni II] identification, it is possible to estimate the Ni abundance in the same way that an Fe abundance was estimated in Paper II. This involves comparing the intensity of the line with its intensity in supernova remnants and assuming that the remnants have the "cosmic" abundance of Ni (Allen 1973). The abundance ratio derived in this way is Ni/O (by mass) ~ 5×10^{-4}. However, there is considerable variation in the strength of the [Ni II] line in supernova remnants. In IC 443, recent spectrophotometry by Fesen (1979) shows that the [Ni II] λ7378 has about the same flux as [Fe II] λ7155, and has about one-tenth the flux of [O II] λ7325. For comparison, our observations in Paper I gave a ratio for 2F4 of [Ni II] λ7378 to [O II] λ7325 of about 1/190, and [Fe II] λ7155 was not seen. We believe that the astrophysics of the production of [Ni II] λ7378 is sufficiently uncertain that no strong conclusion about the nickel abundance in Cas A should be drawn.

The abundance limit set on Fe/O can be converted into a limit on the Fe mass fraction, as described in Paper II. The result is that the mass is less than 0.3% Fe, as compared with cosmic matter, which is 0.16% Fe. Thus the limit on the Fe abundance is close to what would be expected for the "seed" Fe that was part of the star when it initially formed.

The Ca II λ3945 line was not observed in filament 1; the upper limit is 0.4 in the units of Table 3. Considering the strength of the [Ca II] λ7291 line in the fast knot 2F4 (Papers I and II), model C of Raymond (1979) predicts that the strength of the Ca II λ3945 lines should be 0.8. The factor of 2 discrepancy is indicative of the errors involved in our analysis. In particular, [Ca II] λ7291 is a weak line in 2F4, and its intensity may have been overestimated in the photographic data.

As discussed above, the relative intensities of lines of [O I], [O II], [O III], [S II], [Ar III], and [Ar IV] are very similar in filament 1 and in knot 2F4. The relative intensities are always within a factor of 2 of each other. A reasonable deduction is that the abundances of these elements are within a factor of 2 of each other in the two fast knots. A further speculation is that the abundances of other elements are the same in the two knots (which are not adjacent in space; see Paper I). The combined abundance information of the two knots is given in Table 4; this table is an updated version of Table 4 of Paper II. The upper limits on C, Ne, Mg, and Fe are derived from observations of filament 1, while the upper limits on H, He, and N, and the abundances of Ca and Ni are derived from observations of knot 2F4.

IV. ABUNDANCE INHOMOGENEITIES

The basic procedure used in deriving abundances for the fast knots was the same as that used for filament 1. The models are not self-consistent shock models, but are attempts to reproduce the conditions in the emitting region. The knots did show various ratios for the [O I]:[O II]:[O III] lines, but the range of

TABLE 4

ABUNDANCES IN FILAMENT 1 AND KNOT 2F4 RELATIVE TO OXYGEN

Element X	X/O (by mass)	X/O (cosmic)
H	< 0.02	95
He	< 0.42	32
C	< 0.003	0.38
N	< 6×10^{-5}	0.12
Ne	< 0.016	0.16
Mg	< 0.008:	0.06
S	0.13	0.05
Ar	0.01	0.02
Ca	0.0026	0.008
Fe	< 0.004:	0.21
Ni	5×10^{-4}:	0.011

variation was similar to that found in shock models for normal interstellar shocks (Raymond 1979). Thus different shock models were considered for comparison with each knot.

Raymond's models do not include lines of Ar. We estimated the Ar/O ratio in the same way as Peimbert and van den Bergh (1971), i.e., from the ratio of [Ar III] λ7136 to [O III] λ5007. It is assumed that $N(\mathrm{Ar})/N(\mathrm{O}) \approx N(\mathrm{Ar}^{++})/N(\mathrm{O}^{++})$. For the conditions present in the knots, collisional deexcitation is not likely to be an important effect for the lines in question. Thus the line ratio is independent of density and is only weakly dependent on the temperature of the emitting region; we assumed $T = 20{,}000$ K. The atomic data were taken from Osterbrock (1974).

In the analysis of knot KB 33, Raymond's models EE and DD give a reasonable fit to the O line ratios. We note that the shock-model parameters are not relevant to the present comparison. The deduced abundances were essentially the same using either model. The S abundance was obtained from the strength of the [S II] λλ4069–4076 lines, the Ar abundance from the [Ar III] λ7136 line, and the Ca abundance from the [Ca II] λ7291 line. The results are given in Table 5.

The [S II] λλ6716–6731 lines are generally not very useful because collisional deexcitation makes them very density sensitive. The same is true of the [O II] λλ3726–3729 lines. However, given the relative intensities of the red and blue [S II] and [O II] lines, it is possible to derive the density and temperature of the emitting region on the assumption that O^+ and S^+ occur in the same region. We carried out this procedure for filament 1 and for KB 33 using predicted line intensities calculated from a simple (five-level) scheme by Koski (1978). For filament 1, the derived temperature was $T_e \approx 18{,}000$ K and $\log N_e \approx 4.6$. It should be noted that the ratios are not highly temperature sensitive, and $T_e \approx 10{,}000$ K would be within the errors for the observed line intensities. For KB 33, we find $T_e \approx 9000$ K and $\log N_e \approx 4.7$ in the emitting region.

In the [O III] filament, only lines of O have been observed. The relative intensities of the lines are consistent with those of Raymond's (1979) model C. Limits on the Ar and Ca abundances can be obtained from the [Ar III] λ7136 line and the [Ca II] λ7291 line and are given in Table 5. A limit on the S/O ratio can be obtained from the absence of the [S II] λλ4069–4076 lines: it is S/O (by mass) < 0.08. However, we have more sensitive observations in the region of the red [S II] lines than in the region of the blue [S II] lines. An estimate of the ratio of the red to blue [S II] lines can be obtained if the density of the emitting region is known. A density estimate for various values of T_e can be obtained from the observed ratio of red to blue [O II] lines. Over the temperature range 7,500–20,000 K, the predicted ratio of red to blue [S II] lines is in the range 2–4. The limit on the red [S II] lines is <0.3 in the units of Table 2, yielding a limit of <0.15 on the blue [S II] lines. This limit is a factor of 30 stronger than that obtained directly from the observations of the blue [S II] lines, because of heavy obscuration. The resulting limit on S/O (by mass) is 0.003. While the limits on the S, Ar, and Ca in this filament are very strong, the limit on the Ne/O is less stringent. We find Ne/O (by mass) < 1.4.

Abundance estimates for KB 61 were obtained by comparison with Raymond's (1979) model CC. Abundances for Ar and Ca were estimated from the strengths of the [Ar III] λ7136 line and the [Ca II] λ7291 line and are given in Table 5. The blue [S II] lines were not observed, yielding a limit S/O (by mass) < 0.08. On the other hand, the red [S II] lines were observed. An upper limit on the ratio of the red to blue [S II] lines can be obtained by assuming that both sets of lines are in the low-density limit. Over the temperature range 7500–20,000 K, this limiting ratio is equal to 10 (to within a factor of 2). This yields a lower limit on S/O (by mass) of 0.04.

The analysis of knot KB 115 is very similar to that of knot KB 61. Again, Raymond's (1979) model CC can be used for comparison purposes. The only difference from KB 61 is that now only an upper limit on the Ca/O ratio can be obtained. The results are given in Table 5.

The observations clearly show that there are abundance inhomogeneities in the Cas A material. One might expect there to be a correlation between the abundance properties of the knots and their velocities if no mixing had occurred during the supernova expansion. We give the kinematic properties of each knot in Table 6, where V_{rad} is the line-of-sight velocity measured spectroscopically, V_{trans} is the transverse velocity, and V_{tot} is the total space velocity. For knots KB 33, KB 61, and KB 115, V_{trans} is obtained directly from the proper motion measurements of Kamper and van den Bergh (1976), taking the distance to Cas A to be 2.8 kpc (van den Bergh and Dodd 1970). Filament 1 and knot 2F4 are extended features, but can be approximately identified with KB 93 and KB 71, respectively, and the transverse velocities given in

TABLE 5

ABUNDANCES IN THE FAST KNOTS BY MASS

Knot	Ne/O	S/O	Ar/O	Ca/O
Filament 1 (and 2F4)	< 0.016	0.13	0.01	0.0026
KB 33	< 0.4	1.4	0.3	0.2
[O III] filament	< 1.4	< 0.003	< 0.006	< 0.07
KB 61	...	0.04–0.08	0.03	0.006
KB 115	...	0.03–0.14	0.2	< 0.01

TABLE 6

VELOCITIES OF THE KNOTS

Knot	V_{rad} (km s^{-1})	V_{trans} (km s^{-1})	V_{tot} (km s^{-1})
Filament 1	+260:	3750	3760
2F4	−1836	4010	4410
[O III] filament	+2070	2820	3500
KB 33	+1420	4340	4570
KB 61	−2308	3770	4420
KB 115	−2823	8350	8810

Table 6 refer to these knots. For the [O III] filament, there is no proper motion available because it has only recently appeared. The value of V_{trans} was obtained by relating the position of the knot to the overall expansion rate of 0".00324 yr^{-1} given by Kamper and van den Bergh (1976). Velocities for the other knots calculated by this method agree quite well with the velocities given in Table 6. The table shows that there is no correlation between V_{tot} and the abundances. The knots (excluding KB 115) have a small range in velocity, but a large range in abundance. Knot KB 115, with the highest V_{tot}, has a S/O ratio which is intermediate between that of the [O III] filament and KB 33.

V. NEON IN CASSIOPEIA A

Recent observations of Cas A (van den Bergh 1971; Searle 1971; Paper I; this paper, § II) have failed to detect any lines of Ne in Cas A. However, Minkowski (1957) does mention observing [Ne III], although he does not mention the line in his review article of 1968 (Minkowski 1968). In order to settle this question, one of us (R. A. C.) examined Minkowski's spectra of Cas A in the plate vault at Hale Observatories. As noted in § III, his spectra of filament 1 do not show [Ne III] emission, but his spectra of filament 5 do show [Ne III] λ3869. The two spectra N191 and N193 taken on 1953 September 15 and October 13 show the line near the plate limit. There is some ambiguity in the identification because the third, fourth, and fifth orders are superposed in the spectra (see Baade and Minkowski 1954). However, Minkowski's spectrum N210 of filament 5 does not have overlapping orders and the [Ne III] λ3869 line is again present. The [Ne III] λ3968 line does not appear on any of the three plates, but it is predicted to be a factor of 3 fainter than the λ3869 line, and the λ3869 line is very close to the plate limit on all three plates.

Plate N194 of filament 1 and plates N191 and N193 of filament 5 cover the same parts of the spectrum (in third, fourth, and fifth order). Lines of [O I] λλ6300–6363, [O II] λλ 3726–3729, [O III] λλ4959–5007, [S II] λλ4069–4076, and [S II] λλ6716–6731 appear in the spectra of both filaments and have comparable relative intensities. However, the part of filament 5 with [Ne III] λ3869 is relatively weak in [S II] λλ6716–6731, implying a high density. While quantitative information on line intensities is not available for the spectra, we estimate that [Ne III] λ3869 is about a factor of 3 fainter than [S II] λλ4069–4076 (found by comparison with lines with a known intensity ratio). Assuming that model C of Raymond (1979) applies for relative line intensities, we estimate Ne/S ≈ 0.9 in filament 5. The observations indicate that the S/O ratio is similar to that in filament 1, i.e., S/O ≈ 0.1, so that Ne/O ≈ 0.1 in filament 5. The Ne/O ratio is almost certainly higher than that in filament 1.

Unfortunately, we do not know the location of filament 5 in Cas A. Baade and Minkowski (1954) discuss filaments 1, 2, and 3, but in the plate files there are spectra of filaments 1, 3, 4, 5, 6, 8, 9, and 11. These include a combination of fast knots and QSFs. There is no record of the positions of these filaments on the plate envelopes.

In addition to the spectra of filaments, there are about a dozen long-slit spectra of Cas A in the plate files. While these spectra show the usual lines of S and O in the fast knots, lines of Ne are not obviously present.

VI. DISCUSSION

In Paper II (see also Peimbert and van den Bergh 1971; Peimbert 1971; Arnett 1975), it was shown that at least some knot material was made up almost exclusively of heavy elements. In particular, it appeared that O burning to the Si group elements had occurred in this gas. The new observations support this conclusion. We have now observed various knots which appear to have undergone different amounts of O burning. It is clear that the abundances of S, Ar, and Ca (all Si group elements) are related to each other.

In standard models of stellar nucleosynthesis, the ratio of Si group elements to O increases as one goes to denser and higher temperature layers, i.e., as one goes into the stellar interior. This is true whether the burning takes place during quasi-static evolution or during explosive processing. If the supernova expansion is spherically symmetric, the inner parts of the star end up with a lower velocity than the outer parts. The fact that a correlation between abundance and velocity is not observed in the Cas A remnant indicates that non-spherically symmetric motions have taken place.

One possibility is that the basic process of the core collapse leading to an explosion is highly asymmetric. A good example of such a situation is provided by Leblanc and Wilson's (1970) calculations of the collapse of a rotating, magnetized core. They find that the explosion occurs in two oppositely directed jets of material. This jet may be able to break through the surface of the star before it is completely decelerated by its interaction with the surrounding mantle gas. Because there is evidence that no stellar envelope was present on top of the mantle at the time of the explosion, the effects of this jet might be detected in the present fast-moving knots. In fact, there is a jetlike feature in the eastern part of the Cas A remnant (see photographs in Kamper and van den Bergh 1976*a*). The knot KB 115 is out in this jet. However, it is not certain that the distribution of emitting gas is the same as the actual distribution of gas in Cas A. It appears that the knots light up when they interact with dense surrounding gas. The region of emission on the north side of the remnant has remained stationary, while fast knots move through it (van den Bergh 1974). Under these circumstances it is not clear that the apparent jet shows the true location of ejected core material.

Another possible reason for the observed abundance structure is that it is the result of Rayleigh-Taylor instabilities during the expansion of the supernova. It was suggested by Falk and Arnett (1973), Chevalier (1976), and Chevalier and Klein (1978) that this instability resulted in the formation of the knots that are observed in Cas A. Chevalier and Klein (1978) discussed the possibility that for small length scales the instability is damped by radiative effects. In this case, the expanding gas would not be completely mixed, but there might be the inversion of regions of gas with different abundances. This is in accord with the observations that there are clumps of gas with different abundances, but which have probably moved relative to each other.

In comparing the observed abundances with nucleosynthesis calculations, it is now clear that the comparison should be with individual layers within a stellar model. The models of Weaver, Zimmerman, and Woosley (1978) give this information in detail for stars of mass 15 $M_{\odot}$ and 25 $M_{\odot}$. However, the mass of the Cas A progenitor is not known, so we do not know whether the comparison is appropriate. The information given by Weaver, Zimmerman, and Woosley (1978) is for the supernova progenitor star at the end of its hydrostatic burning phases. It has been assumed that no mass loss occurred. On the other hand, the progenitor of Cas A does appear to have undergone considerable mass loss. Despite these problems, we proceed with the comparison of theory with observation. One property of the nucleosynthesis calculations is that at the end of hydrostatic burning, the O-rich region is quite distinct from the "Si" (Si group) rich region. The amount of mass with substantial amounts of both O and "Si" is very small. However, the observations of Cas A indicate that most of the emitting regions contain substantial amounts of both O and "Si."

Weaver and Woosley (1979) have computed the explosive nucleosynthesis which occurs when the supernova shock wave moves through the heavy-element–rich regions of the star. They assume that the explosion is spherically symmetric. It is not clear that this was the case for Cas A. The general effect of explosive processing is to move the element layers out with respect to mass in the star. However, it is possible for some regions to undergo incomplete explosive processing. Thus the zones in Cas A with substantial amounts of O and "Si" may have undergone incomplete explosive oxygen burning.

One aspect of the nucleosynthesis calculations is that O never appears entirely by itself. Other elements (e.g., Mg, Ne, or C) are also present at least at the 10% level. Thus in the [O III] filament, which is very low in "Si," it is predicted that either Mg or Ne lines will eventually be detected. The present limit on the Ne abundance is not very strong (see Table 5).

In summary, the supernova remnant Cas A may provide a direct link between observations and calculations of supernova nucleosynthesis. This work needs to be pursued on three fronts: First, we need more observations of Cas A in order to obtain line intensities in different regions and to detect faint lines. Second, consistent shock models are required in order to give greater confidence in the interpretation of the data. In this way, reliable abundance estimates can be obtained. Finally, a fine grid of stellar-evolution calculations through the supernova stage is required in order to provide abundance predictions. The influence of mass loss on the core evolution may also be important for Cas A.

We are grateful to S. van den Bergh for his continued interest in this work, to B. Katem for his valuable assistance in allowing us to examine R. Minkowski's spectra in the Hale Observatories plate vault, to T. Weaver and S. Woosley for discussions of nucleosynthesis in massive stars, and to J. Barnes and K. Strom for assistance in data reduction. R. A. C. acknowledges the hospitality of the astronomy department at the University of California at Berkeley where he was a visiting lecturer during the fall of 1978. R. P. K.'s research on supernovae is supported by NSF grant AST 77-17600.

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ROGER A. CHEVALIER: Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903

ROBERT P. KIRSHNER: Department of Astronomy, University of Michigan, Ann Arbor, MI 48109