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DISCOVERY OF FAST-MOVING OXYGEN FILAMENTS IN PUPPIS A

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ABSTRACT

A number of faint filaments in the Puppis A supernova remnant have been found to have spectra with strong oxygen lines, extremely weak Balmer lines, and radial velocities greater than 1500 km s^{-1}. These are very different from the bright filaments, which are nitrogen-rich and have velocities less than 300 km s^{-1}. The newly discovered filaments are spectroscopically similar to those found in young, oxygen-rich remnants, as typified by the fast-moving knots in Cas A. We interpret these Puppis A filaments as knots of oxygen-rich supernova ejecta which remain relatively uncontaminated by interstellar material, despite the probable age of Puppis A of several thousand years.

Spectra of the newly discovered filaments show, in addition to strong forbidden lines of [O I], [O II], and [O III], *permitted* lines of O I: λλ7774, 8446. We attribute the permitted lines to recombination of O^+, and we use their strength relative to H to estimate that the O:H mass ratio is about 30.

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

I. INTRODUCTION

The bright optical filaments of the Puppis A supernova remnant (SNR) have a chaotic morphology and are notable for their high nitrogen abundance (Baade and Minkowski 1954; Dopita, Mathewson, and Ford 1977). These are similar to the "quasi-stationary flocculi" in Cas A (Chevalier and Kirshner 1978). The observed velocities in these filaments are modest: less than 300 km s^{-1} (Elliott 1979; Shull 1983). The bright, nitrogen-rich flocculi appear to be relatively tame products of hydrogen burning via the CNO cycle, which were broadcast in episodes of mass loss prior to the supernova, and which are now being excited by a blast wave.

X-ray spectra of Puppis A indicate a more interesting chemistry and give evidence for more advanced stellar evolution. The strong emission lines of oxygen and neon observed from the *Einstein Observatory* crystal spectrometer (Canizares and Winkler 1981) indicate the presence of several solar masses of oxygen and neon in the high-temperature plasma that fills Puppis A. Since only helium burning or later nucleosynthetic processes can produce these elements in quantity, Canizares and Winkler proposed that Puppis A resulted from the explosion of a massive star ($\sim 25\ M_\odot$), perhaps as a Type II supernova.

We have discovered some faint optical filaments in Puppis A which bring the X-ray and optical results into much closer agreement. The spectra of these filaments are dominated by oxygen lines, and the Balmer lines are quite weak. Not only are the usual forbidden lines of [O I], [O II], and [O III] prominent, but permitted O I lines are observed as well. Furthermore, the filaments have radial velocities up to 1500 km s^{-1}. We interpret these filaments to be the last vestiges of nearly pure oxygen ejecta from the core of the supernova star. While most of the core ejecta have mixed with interstellar material to give the enriched plasma seen in X-rays, these few optical filaments have remained more or less intact.

The newly discovered filaments appear to be similar chemically and kinematically to the fast-moving knots in Cas A and to five other SNRs with filaments whose optical spectra are dominated by strong oxygen lines (Dopita and Tuohy 1984; Blair, Kirshner, and Winkler 1983, and references therein). The high velocities (1000–5000 km s^{-1}) and small sizes of these other remnants lead to kinematic ages of less than 2000 years. Puppis A is much larger and older: its angular diameter of about 50′ corresponds to 30 pc at a distance of 2 kpc, and its age is generally estimated at 5000–10,000 years based on the X-ray temperature (Culhane 1977). In all the oxygen-rich remnants we have the rare opportunity of studying relatively pure material from the cores of massive stars, a fact which makes this class of special interest.

II. OBSERVATIONS

As part of a program to study optical filaments associated with X-ray–bright regions, we compared broad-band red (IIIaF + RG610) and green (IIIaJ + GG495) plates of Puppis A, taken at prime focus of the CTIO 4 m telescope. The bright filaments appear on both plates, and all are more prominent in the red than in the green. By contrast, there are several faint filaments which are noticeably brighter in green than in red. The brightest of these can be seen near the center of Figure 1, which shows a region from the interior of Puppis A. This "Ω" filament, as we shall refer to it, is clearly visible on the green plate as an Ω-shaped region of nebulosity just south and east of the indicated star. The position of the star is $\alpha = 8^h20^m57\overset{s}{.}7$, $\delta = -42°41'43\overset{''}{.}7$ (1950). Pairs of plates taken in 1978 and 1984 show essentially the same features. We have chosen the highest quality plates for reproduction in Figure 1: green from 1978 March 1 and red from 1984 February 3.

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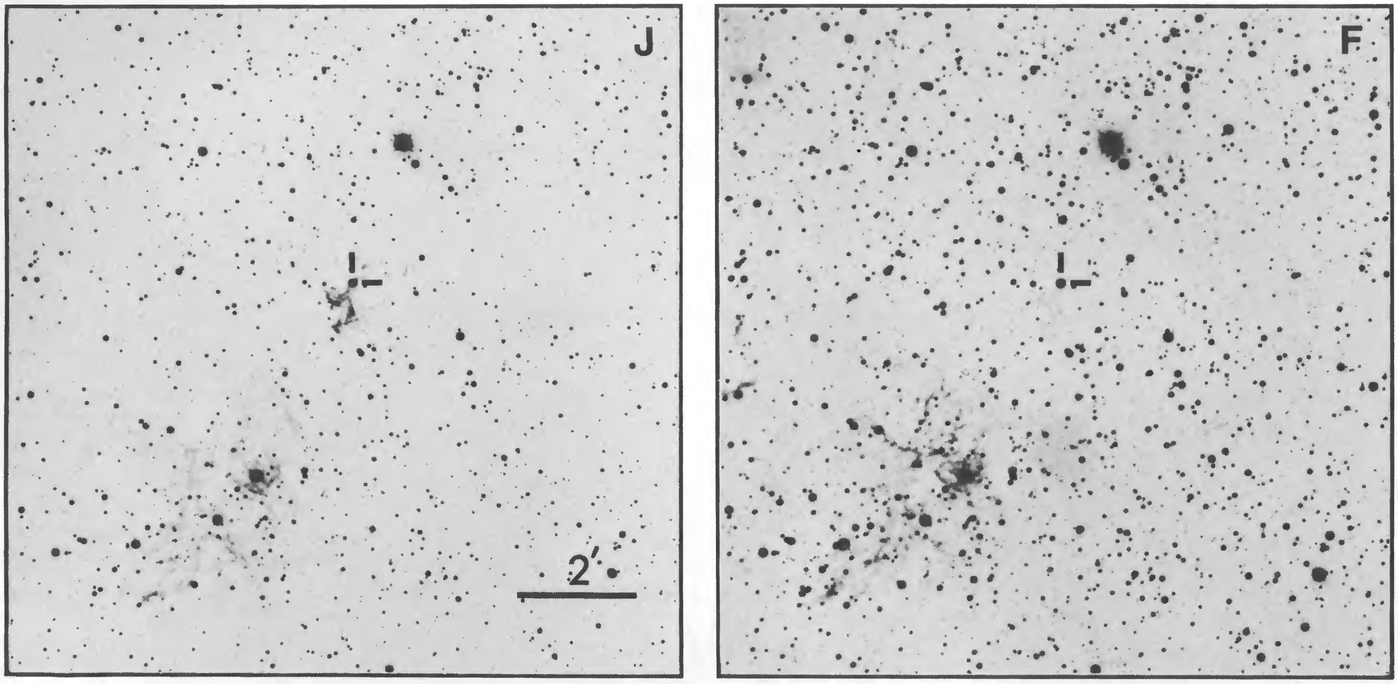

FIG. 1.—Images showing the central region of Puppis A in green (J) and red (F). North is up and east is to the left. Near the marked star, an "Ω" of nebulosity is clearly visible on the green plate; its emission is primarily due to oxygen lines. On the red plate, this filament is nearly invisible, while the other filaments remain prominent due to strong emission in Hα and [N II].

The Ω filament was observed in two runs with the Ritchey-Chrétien spectrograph on the CTIO 4 m telescope. The first observation, 1982 January 18–20, used a 2″.0 slit width and the 40 mm SIT Vidicon to cover the wavelength range 4800–7400 Å with a resolution of 7 Å. An observation on 1984 January 30–31 with the CCD detector (GEC No. 3) and a 1″.3 slit width covered the range 6200–8650 Å with 11 Å resolution. In both observations simultaneous spectra from nearby regions along the 180″ length of the slit were used for background subtraction. Standard reduction techniques have been used to place the spectra on a linear wavelength scale and to reduce them to fluxes.

III. RESULTS

The spectrum from a total of 60 minutes integration with the SIT on the Ω filament is shown in Figure 2*a*. Two systems of lines are present: a faint system at zero velocity, due to overall diffuse emission in the vicinity, and a much stronger system blueshifted by a mean velocity of 1520 ± 40 km s^{-1}. The oxygen lines in the blueshifted system are dramatically strong relative to the Balmer lines; for example [O III] λ5007 is over 100 times the strength of Hβ. The strong [O III] lines account for the prominence of the Ω filament in the green plate of Figure 1.

For comparison, Figure 2*b* shows the spectrum from one of the bright filaments along the northwest rim of Puppis A, integrated for a total of 40 minutes in the same observing run. Located at $\alpha = 8^h20^m4^s$, $\delta = -42°27'15''$ (1950), This is a portion of filament number 4 of Baade and Minkowski (1954). The extreme strength of the [N II] lines is typical of that found in bright filaments of Puppis A (Dopita, Mathewson, and Ford 1977).

The CCD spectrum of the Ω filament, the result of 80 minutes total integration time, is shown in Figure 2*c*. As in the SIT spectrum of Figure 2*a*, the most prominent lines are blueshifted forbidden lines of oxygen. These give a mean velocity of 1570 ± 20 km s^{-1}, consistent with that obtained from the SIT spectrum. Weak Hα and [S II] λλ6716, 6731 and very weak [N II] λ6583 are also seen in the blueshifted system. The apparent absorption features at wavelengths of zero-velocity [O I] (6300 Å) and Hα are due to excess subtraction of diffuse emission from the "sky" regions adjacent to the Ω filament. This entire region of Puppis A has faint, diffuse line emission, as is evident in the deep Hα plate of Goudis and Meaburn (1978).

The most interesting lines in Figure 2*c* are those at measured wavelengths 7733 Å and 8404 Å. We attribute these to *permitted* transitions of O I, λλ7774, 8446 in the blueshifted system. The identification is unambiguous: the blueshifts of the two lines correspond to velocities of 1580 ± 90 and 1490 ± 150 km s^{-1}, in agreement with those obtained from the forbidden lines.

Weak O I λ8446 emission has been observed in several astrophysical locales: the Orion nebula, planetary nebulae, emission-line objects such as SS 433, and Seyfert 1 galaxies (Grandi 1975, 1976, 1980 and references therein). The λ8446 line is very strong in the spectra of some novae, often accompanied by weak O I λ7774 (Strittmatter *et al.* 1977; Gallagher and Starrfield 1978 and references therein). These lines have never been positively identified in the spectrum of any SNR, although Kirshner and Chevalier found a faint suggestion of λ7774 in a single filament of Cas A.

In Table 1 we list the observed fluxes, $F(\lambda)$, and reddening-corrected fluxes, $I(\lambda)$, for the Ω filament and for the more typical filament number 4. All fluxes are scaled relative to Hα = 300. To obtain the reddening correction, we have measured the Hα/Hβ ratio in several filaments of Puppis A where both lines are well observed. Setting the dereddened ratio equal to the recombination value, in the manner of Miller and Mathews (1972), we obtain $E(B-V) = 0.5$, and $A_V = 1.5$. This value for the reddening coefficient agrees well with that obtained from the X-ray absorption measurement of $N_H \approx 3 \times 10^{21}$ atoms cm^{-2} (Winkler *et al.* 1981*b*), which with

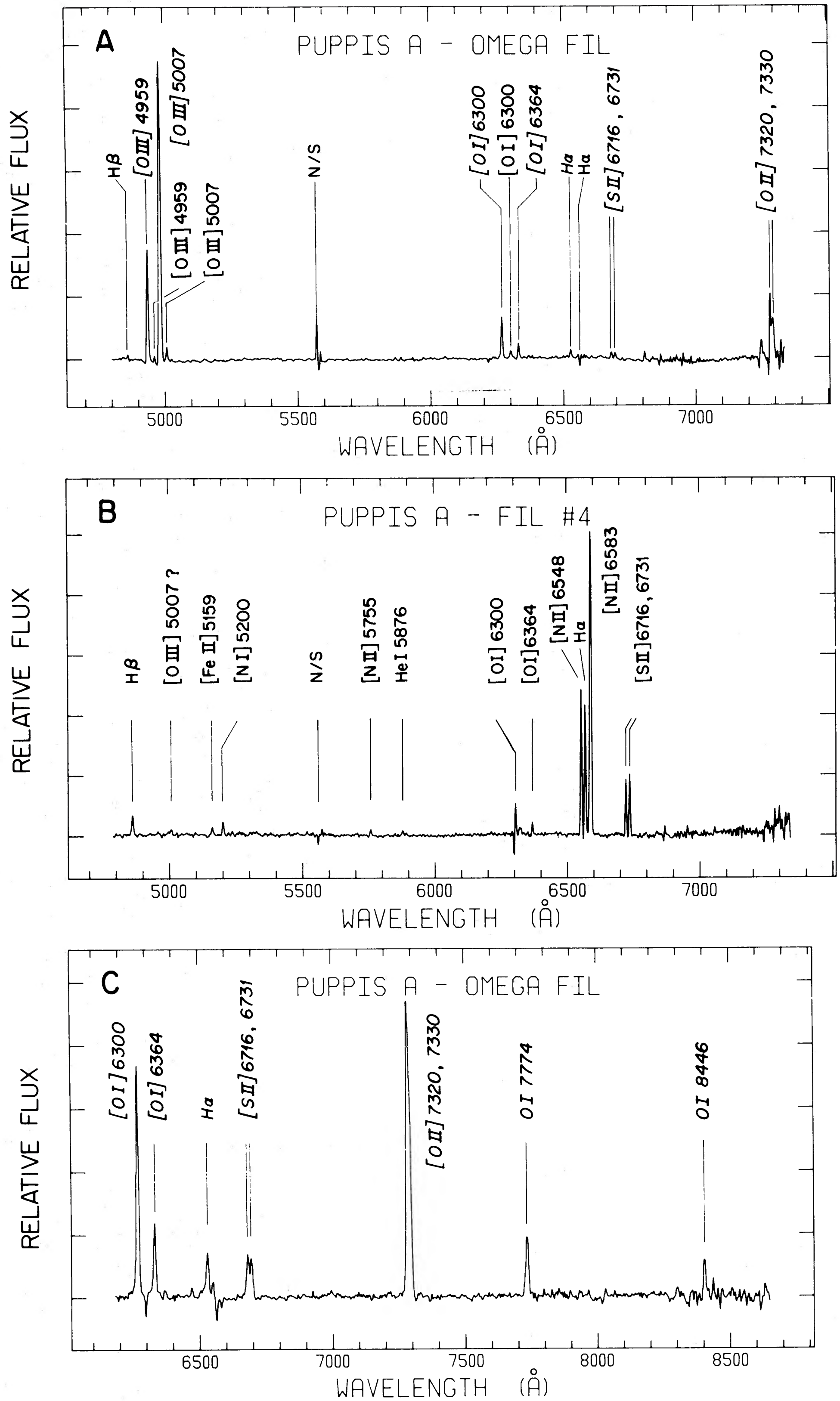

FIG. 2.—(*a*, *top*) SIT spectrum of the Ω filament. The strongest lines are those in the system blueshifted by 1520 km s^{-1} and are identified with slanted legend. Zero-velocity lines, probably due to diffuse emission in the vicinity, are identified in block legend. (*b*, *center*) SIT spectrum of a typical bright filament of Puppis A. (*c*, *bottom*) CCD spectrum of the Ω filament; notation is the same as in (*a*) above.

TABLE 1

LINE STRENGTHS IN PUPPIS A FILAMENTS

		FLUX RELATIVE TO Hα = 300					
		Ω Filament (SIT)		Ω Filament (CCD)		Filament #4 (SIT)	
λ(Å)	ID	$F(\lambda)$	$I(\lambda)$[a]	$F(\lambda)$	$I(\lambda)$[a]	$F(\lambda)$	$I(\lambda)$[a]
4861	Hβ	<120	<200	...	...	54	92
4959	[O III]	4600	7500				
5007	[O III]	14600	23500	...	...	(25)	(40)
6300	[O I]	1530	1630	1310	1390	56	60
6364	[O I]	500	520	440	460	29	31
6548	[N II]	<90	<90	<50	<50	320	330
6583	[N II]	<120	<120	(70)	(70)	920	920
6563	Hα	300	300	300	300	300	300
6716	[S II]	240	230	270	260	110	110
6731	[S II]	200	200	220	210	130	120
7320–30	[O II]	(4000)	(3400)	2690	2300		
7774	O I	...	...	410	320		
8446	O I	...	...	210	150		

[a] Reddening correction assumes $A_v = 1.5$.
Values in parentheses have high uncertainty.

$N_H/E(B-V) = 5.8 \times 10^{21}$ atoms cm^{-2} mag^{-1} (Savage and Mathis 1979) gives $E(B-V) \approx 0.5$.

IV. INTERPRETATION

It is clear that the Ω filament is extremely rich in oxygen. Three lines of argument lead to this conclusion. (1) Lines of [O I], [O II], and [O III] are all observed to be very strong, 5–80 times stronger than Hα, and stronger still compared to lines from any other element. Even without considering the detailed physical conditions, there is no plausible mechanism which can give such strong lines from three ionization states of oxygen, and weak lines from all other elements, unless oxygen is the predominant constituent. (2) The observation of permitted O I lines is most unusual. We argue below that these lines arise from recombination. In a recombining plasma, O^+ must compete with H^+ for electrons, a battle in which hydrogen is usually the victor due to its much greater abundance. Here, however, the O I lines are comparable in strength to Hα, leading us to conclude that oxygen is winning, or at least tying, in the competition; therefore, the oxygen abundance must be vastly enhanced over its normal cosmic value. (3) The Ω filament in Puppis A is similar, both spectroscopically and kinematically, to filaments in other SNRs which have been shown to be oxygen-rich.

We interpret the Ω filament as being made up of relatively cool, dense material which is interacting with the much hotter, more tenuous plasma that fills much of the remnant and is responsible for the X-ray emission. The spectrum of the Ω filament indicates that it is shock-excited. It is very likely that as a knot of supernova ejecta encounters hot, high-pressure plasma, a shock wave will be driven into the knot, and that optical emission lines will result from the cooling region behind the shock. Evaporated material from many knots like the Ω filament could account for the observed enrichment of the X-ray–emitting plasma by more than 2 $M_\odot$ of oxygen (Canizares and Winkler 1981).

Itoh (1981) has calculated models for the optical emission from shocked oxygen-rich ejecta under a variety of conditions. To the extent to which his models and our spectra can be compared, there is reasonable agreement between the spectrum of the Ω filament and Itoh's model G, in which a shock of velocity 141.6 km s^{-1} encounters an oxygen knot with initial density of 30 cm^{-3}. The relative line strengths for [O III] λ4959 + λ5007, [O I] λ6300 + λ6364, and [O II] λ7320 + λ7330 in this model are 100, 10, and 10, respectively, while we have observed relative strengths of 100, 7, and 9 for the filament. Other combinations of density and shock velocity may result in as good or better agreement with this limited data set. We have not yet measured the strong [O II] λ3727 or [O III] λ4363 lines, and Itoh's models do not include intensities for the O I λ7774 and λ8446 lines. While more work on both the observational and the theoretical fronts will afford a more detailed analysis, it is at least plausible that a shock wave in predominantly oxygen material can produce the observed emission from the Ω filament.

a) Oxygen Abundance

A comparison between the permitted lines of O I and the Balmer lines can give us an estimate of the relative abundances of O and H, provided we can show that the O I lines result from recombination. Other possible excitation mechanisms for the O I lines include collisional excitation by electrons and fluorescence based on a coincidence of energy levels between H I and O I. Collisional excitation can be ruled out because the initial states for the O I lines have excitation energies far too high to be appreciably populated at temperatures low enough to maintain a reasonable population of O^0. The O I λ8446 line observed in novae (Strittmatter *et al.* 1977) and in Seyfert 1 galaxies (Grandi 1980) is due in both cases to pumping of this line by Lyβ. This conclusion was reached because the λ7774 line is much weaker than λ8446, whereas in recombination the relative strengths of the two lines should be roughly proportional to their statistical weights: $I(7774)/I(8446) \approx 5/3$. In the present observations the relative strengths of these lines *are* consistent with their statistical weights; furthermore, the H I lines are so weak that pumping by Lyβ is implausible. Therefore, we conclude that recombination is primarily responsible for the O I line emission.

The emissivity in a line corresponding to a transition from level m to level n in O^0 due to recombination of O^+ is $N_{O^+} N_e \alpha_{nm}{}^{\rm eff} h\nu_{nm}$, where N_{O^+} and N_e are the densities of O^+ ions and electrons, respectively, and $\alpha_{nm}{}^{\rm eff}$ is the effective recombination coefficient for events which produce a photon of frequency ν_{nm} either directly or through cascades. The relevant transitions in O I are $2p^3 3s\ ^5S, (^3S) - 2p^3 3p\ ^5P, (^3P)$ for the λ7774 and (λ8446) multiplets.

Julienne, Davis, and Oran (1974) have calculated the effective recombination coefficients at a temperature of 1160 K. We have scaled their values to higher temperatures using the results of Gould (1978), who finds that the recombination coefficients to levels above the ground state scale roughly as $T^{-0.9}$, and we obtain $\alpha_{7774}{}^{\rm eff} = 6.6 \times 10^{-14}$ and $\alpha_{8446}{}^{\rm eff} = 3.6 \times 10^{-14}$ cm^3 s^{-1} for the quintet and triplet states, respectively, at 10^4 K. An estimate based on the relative strengths of O I and [O II] indicates that this is the right temperature range.

For recombination of H^+, Osterbrock (1974) gives $\alpha_{H\alpha}{}^{\rm eff} = 11.7 \times 10^{-14}$ cm^3 s^{-1} at $T_e = 10^4$ K in the optically thick case. (The recombination coefficient in the less likely optically thin case is 30% smaller.) If we assume that the recombination of

O^+ and H^+ is taking place in the same region, then the line strengths give us the relative abundances of these ions directly:

$$\frac{N_{O^+}}{N_{H^+}} = \frac{I(7774)}{I(H\alpha)} \frac{\alpha_{H\alpha}{}^{eff}}{\alpha_{7774}{}^{eff}} \frac{h\nu_{H\alpha}}{h\nu_{7774}} \approx 2.3 .$$

Several factors may affect this estimate: temperature can have only a slight effect since the temperature dependence of the recombination coefficients is very similar; the H^+ and O^+ recombination zones may not coincide exactly; and there could be significant H^+ in hotter regions where the oxygen is ionized to O^{++}.

Nevertheless, the $O^+:H^+$ ratio should give a reasonable measure of the O:H abundance ratio. Our conclusion is that the O:H number ratio is about 2, or an O:H mass ratio of about 30 in the Ω filament! Needless to say, this amounts to a dramatic overabundance of oxygen compared to the normal cosmic value O:H $\approx 8.5 \times 10^{-4}$ by number (Meyer 1979).

b) Kinematics and Age

Previous estimates of the age of Puppis A have been based on the X-ray data. The X-ray spectrum has a hot component with a temperature of 7–12 $\times 10^6$ K (Gorenstein, Harnden, and Tucker 1974; Zarnecki *et al.* 1978; Winkler, Canizares, and Bromley 1983), which corresponds to a shock velocity of 700–900 km s^{-1}. Assuming a distance of 2 kpc and applying the Sedov (1959) model for SNR expansion, one obtains an age of 6000–8000 years.

We can obtain a kinematic estimate of the age by assuming that the fast filaments have suffered negligible deceleration since the supernova event. Several filaments similar to the Ω appear at positions well distributed throughout the Puppis A shell; of these, the Ω has one of the highest radial velocities and appears near the shell center. If we assume that the filament has reached a position near the outside of the shell on the side facing Earth (having spent most of its life coasting toward us through the tenuous interior of the remnant), we find an age of less than about 10^4 years, consistent with the X-ray estimate.

It may be possible to establish the age, and perhaps the distance, of Puppis A more precisely through observations of proper motions and radial velocities of fast filaments. At a distance of 2 kpc, a filament will have a proper motion $\mu = 0.1 v_t/(1000 \text{ km s}^{-1})$ arcsec yr^{-1}, so the transverse velocity v_t may well be measurable over only a few years. A detailed study of the entire system of oxygen-rich filaments is under way and will be reported in a subsequent paper.

Finally, we note that the 1500 km s^{-1} velocity of the Ω filament, while fast compared with other filaments in Puppis A, is slow compared with typical velocities of 5000 km s^{-1} observed in the spectra of Type II supernovae. There is no inconsistency here; the outer layers of ejecta which are observed during a supernova outburst have velocities of $\sim$5000 km s^{-1} and ordinary chemical abundances (Kirshner and Kwan 1975), but 1500 km s^{-1} may be typical of the inner, oxygen-rich zone. The oxygen-rich material catches up with the outer layers and becomes visible only after the latter have been decelerated by sweeping up much interstellar material.

V. OTHER OXYGEN-RICH SNRs

The Ω filament in Puppis A has striking spectroscopic similarities to the six other remnants with filaments whose optical spectra are dominated by strong lines of oxygen. The prototype of this class is the system of fast-moving knots in Cas A, and it has been joined by one other galactic SNR, three in the Magellanic Clouds, and by the bright SNR in NGC 4449. All six have filaments whose spectra indicate that they are chemically peculiar—composed predominantly of oxygen—and all show evidence of high velocities: 1000–5000 km s^{-1}.

TABLE 2

SUPERNOVA REMNANTS WITH FAST OXYGEN FILAMENTS

SNR	Diameter (pc)	Expansion Velocity[a] (km s^{-1})	Kinematic Age[b] (yr)
NGC 4449 SNR	1.6(1)	3500(2)	$\lesssim$200
0540−69 (LMC)	2(3)	1500(3)	600
Cas A	3.5	5000(4)	325(5)
N132D (LMC)	6(6)	2250(6)	1300
1E0102−7219 (SMC)	7(7)	3300(7)	1000
G292.0+1.8	~8(8)	1100(9)	1800
Puppis A	30(10)	1500(10)	10000

[a] Taken as measured velocities of the fastest filaments, or as one-half the full width at zero intensity for broad-line remnants.

[b] Radius ÷ expansion velocity.

REFERENCES: (1) Bignell and Seaquist 1983; (2) Kirshner and Blair 1980; (3) Mathewson, *et al.* 1980, adjusted to $d_{LMC} \approx 55$ kpc; (4) Kirshner and Chevalier 1977; (5) van den Bergh and Kamper 1983; (6) Lasker 1980; (7) Tuohy and Dopita 1983; (8) Goss *et al.* 1979; (9) Braun *et al.* 1983; (10) This paper.

The kinematic properties of all the oxygen-rich SNRs are summarized in Table 2. (See Table 2 of Dopita and Tuohy 1984; Table 3 of Blair, Kirshner, and Winkler 1983; and Table 1 of this paper for the line strengths.) The small sizes and high filament velocities of the six previously known members of this class lead to kinematic ages under 2000 yrs for all of them. The fact that similar filaments of relatively uncontaminated ejecta are found in Puppis A indicates that even a middle-aged remnant can still show traces of youthful vigor—a thought which we find encouraging. Perhaps oxygen-rich filaments can be found in other middle-aged remnants as well.

Of the seven SNRs in Table 2, only Cas A, N132D, and Puppis A have high-resolution X-ray spectra. Like Puppis A, N132D has extremely strong lines of O VIII (Canizares *et al.* 1983); in fact, its X-ray plasma may be even richer in oxygen than is Puppis A's. For Cas A, strong X-ray lines of Si, S, Ar, and Ca were reported by Becker *et al.* (1979), and these elements appear to be unusually abundant in the X-ray plasma. It is likely that the Cas A plasma is enriched in O also, but the interstellar absorption is too great for X-ray lines of O VII or O VIII to have been detectable from the *Einstein Observatory.* At least in the cases of Puppis A and N132D there is a correlation between the composition of the fast oxygen-rich filaments and that of the much larger mass of X-ray emitting plasma. Further investigation may extend this correlation to other members of the class. High-resolution X-ray spectra of young SNRs in our Galaxy and others can yield invaluable information about the chemical composition of supernova ejecta and will be an important study for *AXAF*.

VI. CONCLUSIONS

The spectroscopic evidence indicates that the Ω filament in Puppis is very highly enriched in oxygen. This fact, together with the high radial velocity of this filament (over 5 times faster than those of the ordinary bright filaments), leads us to conclude that the Ω filament is a fragment of ejecta from the core of a massive progenitor star. The discovery of the Ω and other

O-rich filaments in Puppis A fits nicely with the X-ray line spectra reported by Winkler *et al.* (1981*a*): the several $M_\odot$ of oxygen required to enrich the X-ray emitting plasma could have come from the evaporation of large numbers of filaments like the Ω. It will be interesting to look for neon in the fast filaments to see if it too is unusually abundant, as it is in the X-ray plasma. Measurement of proper motions of the entire system of fast, oxygen-rich filaments may lead to an accurate determination of the age and distance of Puppis A. Further spectroscopic and astrometric investigations of these filaments are in progress.

The fast O-rich filaments in Puppis A are similar to those observed in six younger SNR, and in one of these a similar O-enrichment of the X-ray plasma is also seen. SNR filaments with extreme abundances provide the most direct evidence for heavy-element enrichment by supernovae (Fowler 1984). Such filaments provide our closest observational glimpse at material from the interiors of highly evolved massive stars. Systematic study of the chemical composition of these unusual SNRs, and comparison with theoretical models for the stars that produce them, is an important avenue for future supernova research.

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