NON-EQUILIBRIUM IONIZATION IN PUPPIS A

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ABSTRACT

High resolution X-ray spectroscopy of the brightest knot of emission in the Puppis A supernova remnant shows that it is made up of ionizing plasma, far from equilibrium. Flux measurements in several X-ray lines enable us to determine the non-equilibrium conditions: electron temperature, ion populations, and time since the knot was heated by the supernova shock. Imaging and spectroscopic data from the Einstein Observatory together suggest that this knot is a cloud of density about 10 cm^{-3} which has recently been shocked to a temperature 7×10^6 K. Radio and optical data on the region appear consistent with this picture.

INTRODUCTION

A recurring theme of this meeting and of recent literature on supernova remnants (SNR) is the importance of non-equilibrium ionization (NEI) in interpreting X-ray spectra. The time scales for oxygen and heavier elements to achieve ionization equilibrium in shocked plasmas are often greater than the ages of young SNR. The X-ray spectrum, consisting primarily of lines from highly stripped ions, will be significantly different from that of an equilibrium plasma (e.g., as calculated by Raymond and Smith 1977 or Shull 1981) both because the ion populations in an NEI plasma are different from those at equilibrium, and also because in an ionizing plasma the emissivities of many lines are enhanced over their equilibrium values. These effects may reduce the extremely high heavy-element abundances that have been inferred from equilibrium-model fits to the X-ray spectra of several young SNR (Shull 1982 and references therein).

We present here the first clear measurements of NEI conditions in an SNR. These have been carried out for a bright knot of plasma located just behind the shock front in Puppis A, using data from the Focal Plane Crystal Spectrometer (FPCS) at the Einstein Observatory.

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Puppis A is extremely rich both in its X-ray line spectrum and in its spatial structure. We have already published analysis of the spectrum from the interior region of Puppis A (Winkler et al. 1981a, 1981b, 1982; Canizares and Winkler 1981; Canizares et al., this meeting). Here we will discuss new results from observations of the "bright eastern knot" of X-ray emission discussed by Petre et al. (1982 and this meeting). This knot, centered at $\alpha = 8^h22^m30^s$, $\delta = -42^o48'$ (1950), has the highest X-ray surface brightness of any feature in Puppis A. This knot lies just inside the shock front, and both X-ray and radio maps show a steep intensity gradient separating it from the unshocked ISM to the east. Furthermore, the SNR shell appears to have been retarded where it meets the knot. These facts suggest that the knot is a recently shocked cloud with density ~10 cm^{-3}.

Several important energy bands of the spectrum from the bright eastern knot were scanned with the Einstein FPCS in a series of observations during November 1979 and June 1980. The 6' circular aperture of the FPCS, used in all these observations, defined a field which matched the size of the knot well. The composite spectrum of the eastern knot is shown in Figure 1, which may be compared with that from the interior of Puppis A in Figure 1 and 2 of Winkler et al. 1981a. In both spectra the predominant ions are O VII, O VIII, Ne IX, Ne X and Fe XVII; however, there are important differences in the relative strengths of lines from these ions, as we discuss below.

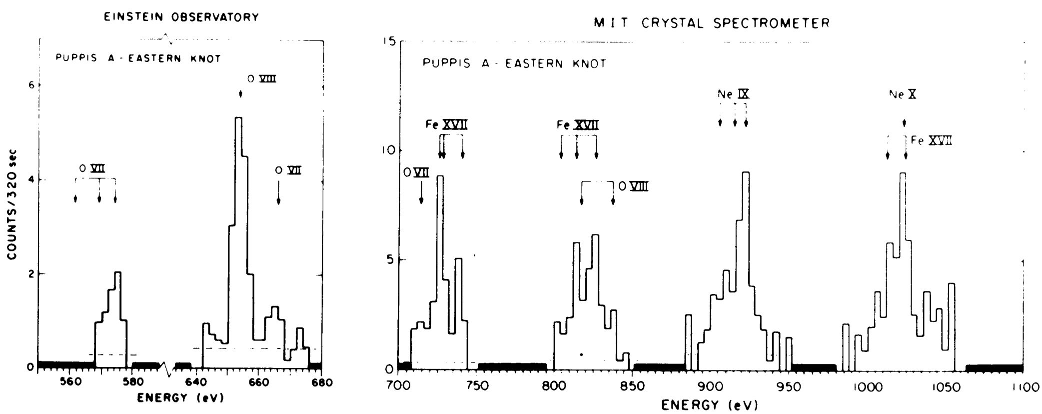

Figure 1. X-ray spectrum of the Puppis A bright eastern knot as observed with the Einstein FPCS. Count rates have not been corrected for instrumental efficiency.

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PLASMA DIAGNOSTICS

Since the FPCS enables us to measure directly the flux in numerous spectral lines, we can use ratios of line strengths as diagnostics for several important properties of the emitting plasma. (See Winkler et al. 1981b, 1982 for a more complete discussion.) The flux in any line can be written as a product of several factors; e.g., for O VIII Lyman α:

$$F = \underbrace{\left(\frac{n_{O+7}}{n_O}\right)}_{\text{ion fraction}} \times \underbrace{\left(\frac{n_O}{n_e}\right)}_{\text{oxygen abundance}} \times \underbrace{\Omega_{L\alpha}}_{\text{collision strength}} \times \underbrace{e^{-E_{exc}/kT_e}}_{\text{temperature}} \times \underbrace{e^{-\sigma_E N_H}}_{\text{absorption}} \times \underbrace{\int n_e^2 dV}_{\text{emission integral}} \times \underbrace{\frac{1}{4\pi d^2}}_{\text{distance}}$$

Most of these factors involve quantities which are poorly known, but by taking line flux ratios we can eliminate many of the unknowns.

A. Electron Temperature and Column Density

The first diagnostic uses ratios of different lines from the same ion to determine the electron temperature T_e and the absorption column density N_H. In taking the ratio, all the factors in the flux equation cancel except for the third, fourth and fifth. If the collision strengths are known (we have used those from Shull 1981), then each ratio leads to an allowed region in the T_e-N_H parameter space.

Five different ratios can be formed from lines observed in the eastern bright knot of Puppis A, as listed in Table 1.

Table 1. Puppis A - Eastern Knot

Ratio	Lines and Energies[a]	Observed Value
O VII BA	Heβ (666eV)/Heα (574eV)	0.45 ± 0.17
O VIII CA	Lγ (817eV)/Lα (654eV)	0.24 ± 0.08
Fe XVII BA	$2p^5 3d$(802-826eV)/$2p^5 3s$(725-739eV)	1.51 ± 0.36
Fe XVII CA	$2p^5 4d$(1011-1023eV)/$2p^5 3s$	0.19 ± 0.10
Fe XVII CB	$2p^5 4d/2p^5 3d$	0.29 ± 0.15

[a]See Winkler et al. (1983) for complete spectroscopic identification and line fluxes.

Some of the lines are blends only partially resolved by the FPCS, e.g., Fe XVII lines at 802, 813, and 826 eV are blended with O VIII Lγ and Lδ at 817 and 837 eV. In such cases, we have achieved deblending by fixing the relative strength of members of the same "multiplet" (e.g., O VIII Lδ relative to Lγ) at the theoretical value and varying the total strength of the different multiplets (e.g., O VIII vs. Fe XVII) relative to one another to obtain the best fit to the observed spectrum.

The five ratios yield quite a narrow region of intersection in the T_e-N_H parameter space. In Figure 2 we have plotted the 90 percent-confidence limits for all ratios except Fe XVII BA, which does not further restrict the region of intersection and is thus omitted for simplicity. The column densities allowed to the eastern knot are consistent with the range obtained by Winkler et al. (1981b) to the interior of Puppis A.

B. Ion Populations

A second diagnostic gives the relative population of different ions of the same element by comparing lines from these ions. We have done this for oxygen and neon in the Puppis A eastern knot. The ratio of the 666 eV O VII line to O VIII Lα at 654 eV indicates that

$$n_{O^{+6}}/n_{O^{+7}} = 0.5 \pm 0.2 \quad (2a)$$

For neon the ratio of similar ions gives

$$n_{Ne^{+8}}/n_{Ne^{+9}} = 2.0^{+1.5}_{-1.0} \quad (2b)$$

For a plasma <u>at equilibrium</u> any ion population ratio measures the temperature, but the oxygen and neon ratios lead to different temperatures 2.4×10^6 K and 3.2×10^6 K, respectively. Thus, these populations are incompatible with a plasma at equilibrium.

We can investigate NEI conditions by considering the transient ionization populations of oxygen and neon behind a shock. In a simple model we have assumed the sudden heating of electrons in a plasma cloud to a temperature T_e as a shock passes. The ion populations are then calculated as a function of time after the shock has passed for different values of T_e. It is convenient to use the parameter $n_e t$ as the independent variable since the ionization rate equations then become independent of electron density n_e.

Each measurement of an ion population ratio leads to an allowed band in the parameter space of T_e vs. $n_e t$, as shown in Figure 3. For our measurements of the oxygen and neon ratios (Eq. 2), the bands do not overlap at times long enough to be near equilibrium which reflects the different ionization temperatures. However, in a rapidly ionizing plasma at $T_e \gtrsim 6 \times 10^6$ K oxygen ionizes enough faster than neon to achieve the observed ionization structure in a region indicated in the figure. The shock passage must have been relatively recent: $n_e t \lesssim 10^3$ cm^{-3}yr.

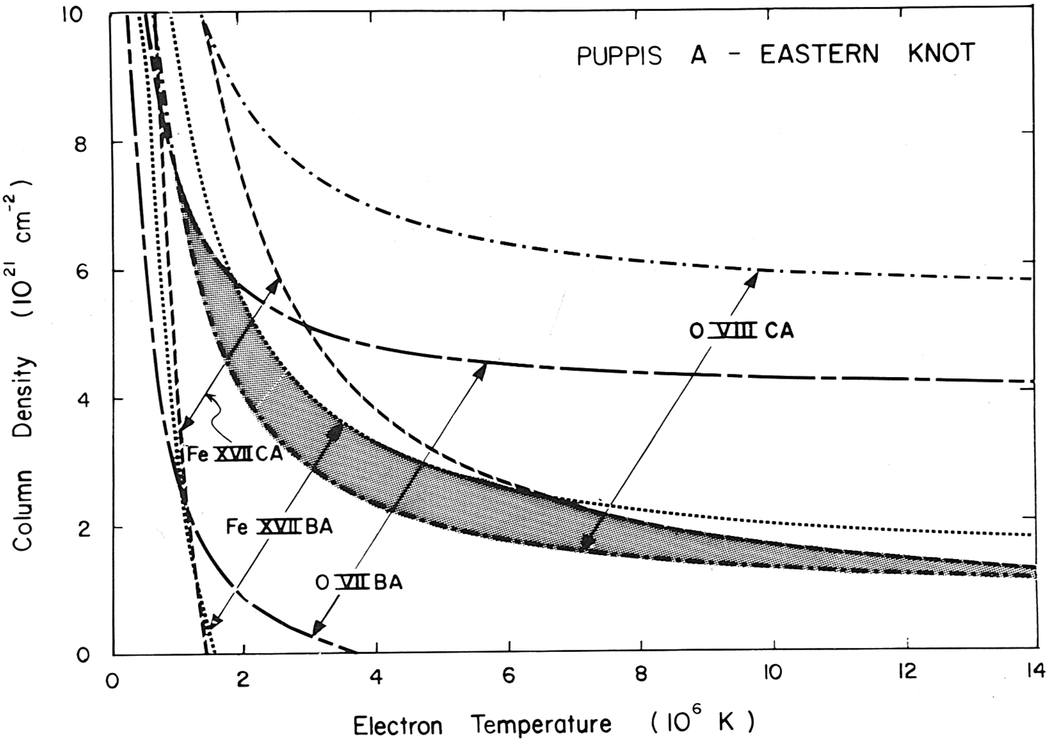

Figure 2. Allowed regions (90% confidence) in T_e - N_H parameter space from four independent line ratios. Shaded area indicates region of overlap.

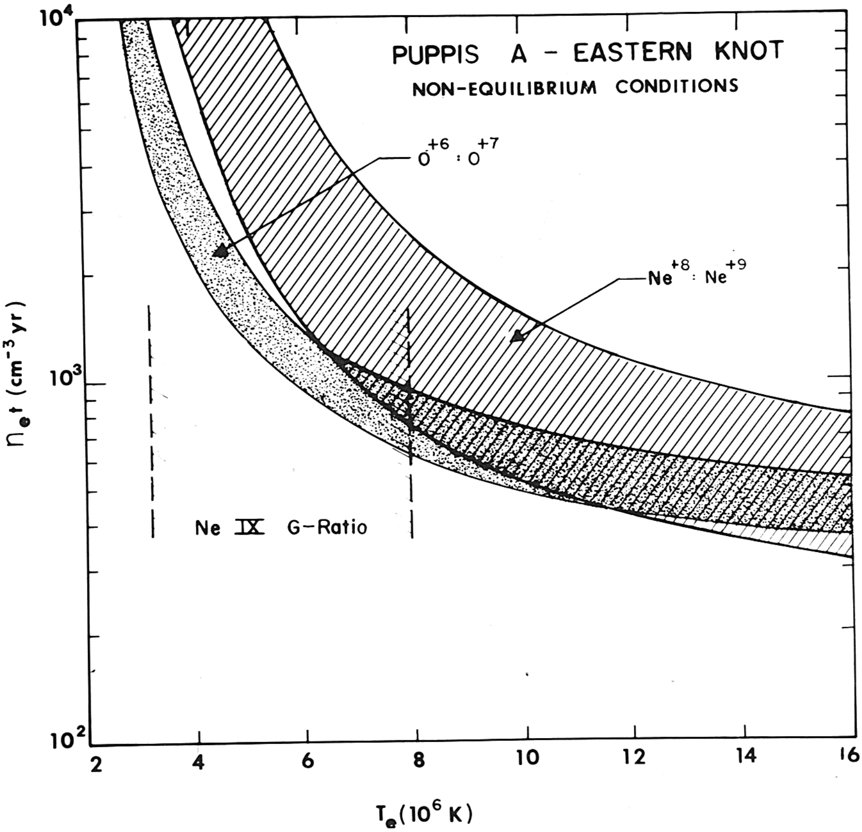

Figure 3. Post-shock transient ionization conditions in bright eastern knot of Puppis A as determined from O and Ne ion populations. Only small triangle at $T_e \simeq 7 \times 10^6$K, $n_e t \simeq 10^3$ cm^{-3}yr is consistent with all the data.

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C. He-like Triplets

A third diagnostic that enables us to restrict further the NEI conditions is the ratio G between different members of the triplet of lines from helium-like ions (Canizares et al., this meeting, and references therein). From the eastern knot in Puppis A we observe G = 0.7 ± 0.2 for the Ne IX triplet. The calculations of Pradhan (1982) show that for an ionizing plasma (no recombination) an electron temperature $T_e = 3 - 8 \times 10^6$ K would give G values for Ne IX consistent with our observations. (See Figure 1 of Canizares et al., this meeting, for details of the same method with the O VII G-ratio, which was not measured in the eastern knot.)

CONCLUSIONS

We can now combine information from all three diagnostics not only to conclude that the eastern bright knot of Puppis A has not reached ionization equilibrium, but also to obtain a relatively precise measurement of the NEI conditions there. When the restriction on T_e from the G-ratio is added to Figure 3, only a very small region of parameter space is allowed: $T_e = 7 \pm 1 \times 10^6$ K, $n_e t = 1.0 \pm 0.2 \times 10^3$ cm^{-3} yr. Furthermore, the narrow range for T_e restricts the allowed column density in Figure 2 to values $N_H \simeq 2 \times 10^{21}$ cm^{-2}. The X-ray spectra indicate that the eastern bright knot in Puppis A has been shocked in the relatively recent past, that the electron temperature is high, and that rapid ionization is still taking place.

The measurement of NEI conditions in the eastern knot is a nice complement to the conclusion by Petre et al. (1982 and this meeting) that the knot is a recently shocked cloud of density $n_e \simeq 10$ cm^{-3}. If the electron temperature results from shock heating, a shock velocity $v_s \simeq 700$ km s^{-1} is required. Since the NEI conditions indicate that $n_e t \simeq 10^3$ cm^{-3} yr, a plasma with $n_e \simeq 10$ cm^{-3} must have been shocked about 10^2 years ago. The shock would have since traversed a characteristic distance $v_s t \simeq 0.1$ pc, comparable to the sizes of bright features in the eastern knot.

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REFERENCES

Canizares, C.R., and Winkler, P.F. 1981, Ap. J. (Letters), 246, L33.

Petre, R., Canizares, C.R., Kriss, G.A., and Winkler, P.F. 1981, Ap. J., 258, 22.
Pradhan, A.K. 1982, Ap. J., 263, 477.
Raymond, J.C., and Smith, B.W. 1977, Ap. J. Suppl., 35, 419.
Shull, J.M. 1981, Ap. J. Suppl., 46, 27.
Shull, J.M. 1982, Ap. J., 262, 308.
Winkler, P.F., Canizares, C.R., Clark, G.W., Markert, T.H., Kalata, K., and Schnopper, H.W. 1981a, Ap. J. (Letters), 246, L27.
Winkler, P.F., Canizares, C.R., Clark, G.W., Markert, T.H., and Petre, R. 1981b, Ap. J., 245, 574.
Winkler, P.F., Canizares, C.R., Markert, T.H., and Szymkowiak, A.E. 1982, in Supernovae: A Survey of Current Research, Proceedings of the NATO Advanced Study Institute held at Cambridge, UK, June 29-July 10, 1981, M.J. Rees and R.J. Stoneham, eds. (Dordrecht: D. Reidel), 501.

DISCUSSION

RAYMOND: Did you assume a single value of $n_e t$ for the entire feature?

WINKLER: Yes. Clearly this model is over-simplified, and we intend to refine it by averaging over material at different ages and distances behind the shock.

MURDIN: This spot is concident with Filament 37 in Puppis A which has the strongest [Fe XIV] line I've seen in an SNR, with strong spatial stratification of the ionic species. I think this fits nicely with your model of a shock wave encountering a blob of material.

WINKLER: Quite so. It's especially interesting that the optical [Fe XIV] filaments as mapped by Dopita et al. match the X-ray structure of the eastern knot in detail. This may enable us to model the iron ionization structure.