HIGH RESOLUTION X-RAY SPECTRA OF SUPERNOVA REMNANTS

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ABSTRACT

We review results obtained with the Focal Plane Crystal Spectrometer (FPCS) on the Einstein Observatory. Clear evidence is found for departures from ionization equilibrium in the interior of Puppis A. This comes from the observed weakness of the forbidden lines relative to the resonance lines for the He - like triplets of O VII and Ne IX. However, it is shown that this departure from equilibrium does not alter our conclusion, based on previous FPCS results, that O and Ne are overabundant relative to Fe. The spectrum of N132D shows strong O VIII emission and very weak Fe emission, suggesting an even greater O/Fe abundance enhancement than in Puppis A. In the Cygnus Loop, the O to Ne abundance ratio is approximately solar; we have no information about Fe. The O VII triplet shows clear evidence for departures from ionization equilibrium in the Cygnus Loop. The spectrum of Tycho's SNR contains lines from ionization stages of Fe XVII through Fe XXIII and XXIV, indicating that a wide range of ionization conditions are present. Cas A and Kepler's SNR show relatively less emission from the higher ionization stages. For Tycho, we measured the strength of the strong Si XIII lines, and we find that a many-fold overabundance of Si relative to Fe is required regardless of the equilibrium state of the emitting plasma (confirming the Solid State Spectrometer results). On a separate topic, the completed analysis of X-ray Doppler shifts in Cas A suggests that the emitting material is concentrated in a ring that is inclined to the line of sight and is expanding at ~5000 km s^{-1}.

INTRODUCTION

This paper will give a status report of the work on Supernova Remnants (SNRs)that we have been carrying our with the X-ray data from the Focal Plane Crystal Spectrometer on the Einstein Observatory. The reasonably high spectral resolution of our instrument allows us to apply plasma diagnostic techniques similar to those used to study laboratory plasmas and the solar corona: we can measure individual line strengths and take selected line ratios to deduce the physical properties of the emitting material (e.g., see Winkler et al. 1982 and

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 205–212.

references given below). Although we are limited by sensitivity and by the necessity of measuring lines one at a time, we have acquired data on most of the brighter SNRs. Our analysis is far from complete, but several interesting results have already emerged. First we will address questions of elemental abundances, which inevitably includes the topic of nonequilibrium ionization, and then we will review our data on the X-ray Doppler shifts in Cas A.

ABUNDANCES AND IONIZATION DISEQUILIBRIUM

Puppis A has by far the richest and brightest X-ray spectrum, an appropriate complement to its spectacular X-ray image (Petre et al. 1982, also, Petre et al. this conference). We have already published some of our analyses of the spectrum of the interior region, which undoubtedly contains a mixture of supernova ejecta and swept-up interstellar material (Winkler et al. 1981a, 1981b, 1982, Canizares and Winkler 1981). In a separate presentation, we give some new spectral results for the eastern bright knot, which appears to be a recently shocked interstellar cloud (Winkler et al., this meeting).

In our work on the interior of Puppis A, a major conclusion was that the O/Fe and Ne/Fe abundances are enhanced relative to cosmic abundances (Canizares and Winkler 1981). We most plausibly attribute this to enrichment by a type II SN in a 20-25 $M_{\odot}$ star. Our analysis was based on a comparison of the ratios of selected O, Ne, and Fe lines both to ratios computed theoretically for equilibrium plasma and to similar ratios observed in solar active regions. Here we explore further the question of ionization equilibrium. We now have good evidence for the departure from equilibrium of the emitting plasma, but we can also strengthen our previous conclusion that the abundance determinations are unaffected.

The evidence for departures from equilibrium comes from an examination of the relative strengths of the closely spaced triplet of lines emitted by He - like ions, such as O VII and Ne IX. The ratio G of the Forbidden ($F:1s^2$ - $1s2s\,^3S$) plus Intercombination ($I:1s^2$ - $1s2p\,^3P$) lines to the Resonance ($R:1s^2$ - $2s2p\,^1S$) line depends on electron temperature and on the importance of recombination vs. collisional excitation for populating the excited states. Recombination cascades favor the ^3S and ^3P states over the ^1S state (because of the statistical weights). A plasma at equilibrium has a given contribution from each process, but in an ionizing plasma the recombination term is suppressed giving smaller F and I lines relative to the R lines (smaller G). Pradhan (1982) has calculated the line strengths and found values that agree very well with solar data (e.g., McKenzie and Landecker 1982). In contrast, for the Puppis A interior one would expect G ~ 1 for O VII in an equilibrium plasma at an electron temperature similar to our observed ionization temperature ($T_i \sim 2\text{-}3 \times 10^6$K), but we see $G \simeq 0.32^{+0.16}_{-0.12}$ implying that the plasma is ionizing with $T_e > 5 \times 10^6$K (See Figure 1). A similar result is found for Ne IX. This is the first clear evidence for non-equilibrium conditions in an SNR.

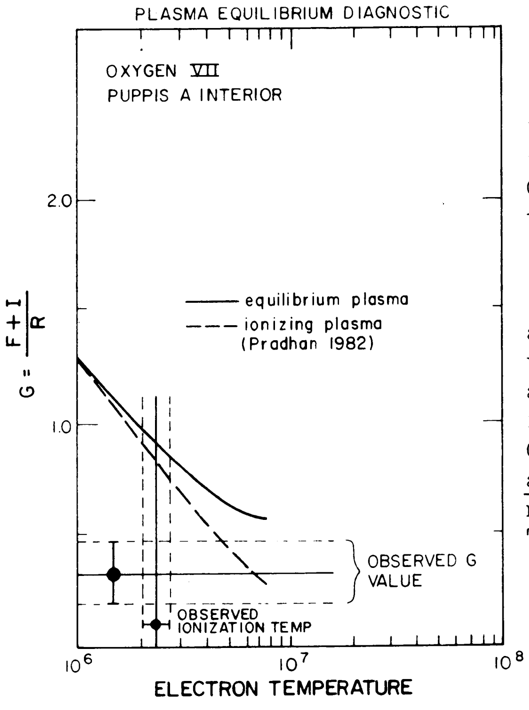

Figure 1: Plasma equilibrium diagnostic for the interior of Puppis A using the ratio Forbidden (F) + Intercombination (I) to Resonance (R) line strengths of O VII (see text). The curves show the calculated ratios from Pradhan (1982) for equilibrium plasma (solid) and for an ionizing plasma (dashed; the recombination terms are suppressed). The observed value with $\pm$ 1 σ errors is shown, as is the observed oxygen ionization temperature derived from O VII/O VIII line ratio (Winkler *et al.* 1981a). Clearly the plasma must be out of equilibrium with $T_e > 5 \times 10^6$K.

Although the establishment of ionization disequilibrium is important for the interpretation of SNR spectra in general, it has little effect on our deduced relative abundances. The reason for this is that the ratio of two lines of similar energy from different elements (e.g., O VIII Lβ at 755 eV to Fe XVII $2p^6 - 2p^5 3d$ at 825 eV) depends on the relative abundances and the ionization fractions for each element but has no other significant dependence on T_e (e.g., see eq. 1 in Winkler *et al.* 1981a). Thus the abundances can be determined once the ionization fractions are known. The ionization fractions can be found from ratios of lines at approximately the same energy from different ionization stages of the same element. For the interior of Puppis A, we find that oxygen is 60% O VIII and 40% O VII (Winkler *et al.* 1981b; we can safely take the O IX fraction to be <10% and the fraction of stages below O VII to be zero). Iron is largely in the form of Fe XVII because the lines of Fe XVIII (~850 - 870 eV) and Fe XX (~960 - 970 eV) are very weak (Canizares and Winkler 1981). These values give the excess O/Fe and Ne/Fe abundance ratios independent of assupmtions about ionization equilibrium. Finally, to drive the point home, we have made a preliminary analysis of our Puppis A data using the models of Hamilton, Sarazin and Chevalier (1982) for non-equilibrium plasma in a Sedov phase SNR. Again, the loci of model

https://doi.org/10.1017/S0074180900033891 Published online by Cambridge University Press

parameters required to explain the O and Ne line ratios do not intersect those required by the O/Fe line ratios unless the O/Fe abundance is several times the solar value.

The remnant N132D in the LMC is known to contain O rich optical filaments (Lasker 1978) and to be very luminous in X-rays (Long, Helfand and Grabelsky 1981). Some of our FPCS data is shown in Figure 2. The spectrum is dominated by the O VIII Lα line -- nearly 10% of

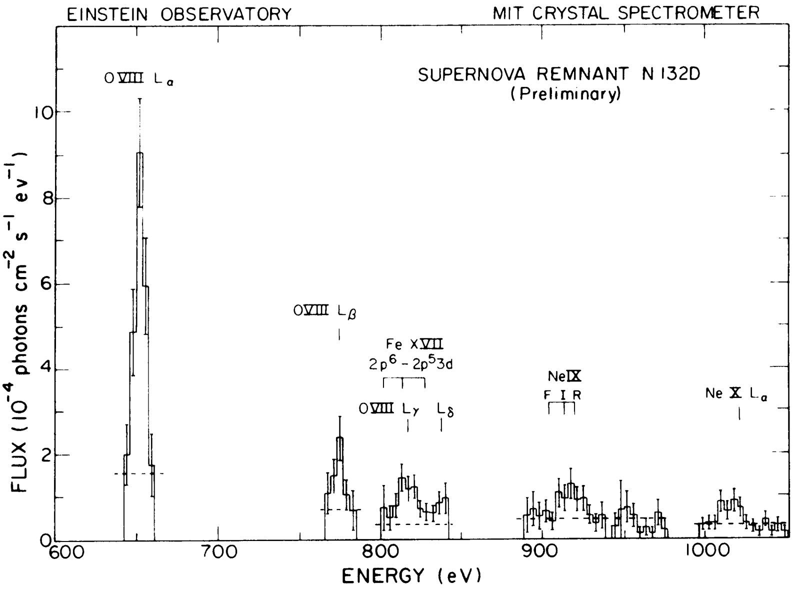

Figure 2: A portion of the X-ray spectrum of N132D corrected for instrumental efficiency.

the total luminosity of the source is in this one feature. By comparison, the Fe XVII line is still weaker than in Puppis A; it may not even be detected (we are exploring the likely possibility that the emission around 826 eV is largely due to O VIII L_γ and $L\delta$). A large O/Fe excess throughout the remnant appears to be inevitable. The enhancement factor will come out of our full analysis. Because N132D may be younger than Puppis A (Lasker 1980), we are probably seeing less diluted ejecta and would expect a larger enhancement if the progenitors of the two SNRs are similar.

Our observations of the Cygnus Loop were confined to a bright region along its northern limb. Peter Vedder has measured fluxes for 6 lines of O VII, O VIII and Ne IX. Unfortunately we did not observe Fe XVII. The O VII/O VIII ionization temperature is ~3 x 10^6K. However, as in Puppis A, the F/R ratio for O VII is smaller than expected for ionization equilibrium implying that T_e must be higher and

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the plasma is still ionizing. This is firm evidence for the importance of nonequilibrium effects even for older SNRs like the Cygnus Loop as was first recognized by Itoh (1979 and references therein).

For the younger remnants Tycho, Kepler and Cas A, we have made systematic observations of the line complex around 1 keV (most of the lower energy lines we describe above are not detectable because of the large interstellar absorption). Although the lines in this region are too closely spaced to be fully resolved, we can separate the various line blends from ionization stages of Fe XVII through Fe XXIV. Our analysis is far from complete, but examination of this complex should be very important for establishing the degree of departures from equilibrium ionization (e.g., see Hamilton, Sarazin and Chevalier 1982). This will help constrain the abundances derived from SSS data (see Holt and Shull, this conference).

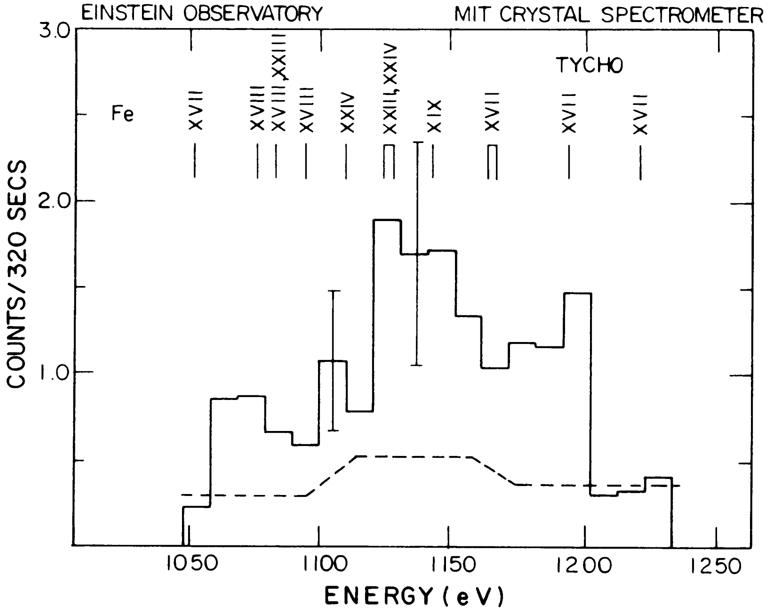

Figure 3: A portion of the X-ray spectrum of Tycho's SNR uncorrected for instrumental efficiency. Location of Fe lines seen in solar flare spectra have been marked (McKenzie et al. 1980).

Figure 3 shows the spectrum of Tycho around 1 keV. A preliminary analysis shows that Tycho has considerably more emission from the higher ionization stages of Fe XXIII and XXIV than do Kepler or Cas A. Note that this would not be reflected in the SSS fits, which give very similar temperatures for the line emitting material in all three SNRs; Becker et al. 1979, 1980a, 1980b. The Fe XVII lines are also present in Tycho, implying that a wide range of ionization is present.

In addition to the Fe lines and blends, for Tycho we have measured the strength of the Si XIII line that is so prominent in the SSS spectrum (Becker et al. 1980b). Even a qualitative examination confirms the SSS conclusion that Si must be overabundant in Tycho: none of the equilibrium models of Raymond and Smith (1977, 1979) or the nonequilibrium models of Hamilton, Sarazin and Chevalier (1982) can come close to reproducing the Fe and Si lines unless the Si abundance is very considerably enhanced (see also Shull, this conference).

X-RAY DOPPLER SHIFTS IN CAS A

We have recently completed our analysis of the X-ray Doppler shifts of Si and S lines from Cas A (Markert et al. 1983). The lines show broadening corresponding to ~5000 km s^{-1} (FWHM) and a northwest/southeast asymmetry of 1820 ± 290 km s^{-1}. Clearly the bulk of the X-ray line emitting material has velocities comparable to those of the fast moving optical knots (van den Bergh 1971), giving a kinetic energy ~4 x 10^{51}erg s^{-1}. The remnant is probably still in its free expansion phase with the X-ray line emission coming from reverse shocked stellar ejecta. The NW/SE asymmetry and the X-ray image (Fabian et al. 1980) can be reconciled with a model in which this emitting material partially fills a ring that is inclined to the line of sight and expanding at ~5000 km s^{-1}. The asymmetric range of optical radial velocities for the NW filaments (van den Bergh 1971) are also consistent with this picture. Such a ring may be the result of an inhomogeneity in the circumsource medium into which Cas A is expanding. An excess density could be caused by equatorial mass loss from the pre-supernova star, for example, which would drive the reverse shock faster and thus deeper into the dense stellar ejecta. An alternative explanation is that the ejecta themselves are preferentially located in the equatorial plane of the rapidly rotating pre-supernova star. This was suggested by Weaver and Woosley (1980). Similar ring-like geometries are seen in two other members of the class of oxygen rich SNRs, N132D (Lasker 1980) and G 292.0+1.9 (Tuohy, Clark and Burton 1982). It may be that this class shares common dynamics as well as elemental composition, and that it represents the remnants of massive stars.

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DISCUSSION

DANZIGER: Are you prepared to make a quantitative statement about Nitrogen in Puppis A?

CANIZARES: No. Unfortunately our instrument was quite insensitive at the energies of the nitrogen lines and so we did not even attempt a measurement. This will have to wait for AXAF.

TUOHY: There are presently 6 oxygen rich SNRs known in our galaxy and in other galaxies. For the 4 SNRs of this group for which we have sufficient velocity or spatial information, each shows evidence for an asymmetric Type II supernova explosion. In particular, there is evidence for expanding rings of ejecta in N132D, G292.0+1.89 and 1E0102.2-72.3, similar to the expanding ring of X-ray ejecta reported for Cas A.

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SARAZIN: You did not mention SN1006 where there is a claim of a possible detection of very strong oxygen emission by Galas et al. Do you have a good limit on oxygen lines from SN1006?

WINKLER: With the FPCS we searched for O VII and O VIII emission from the bright southwest limb of the SN1006 shell, and detected nothing. Scaling our upper limits to the entire remnant (using the Einstein HRI image) gives 3σ upper limits for both the O VII (561-574 eVs) and O VIII (654 eV) lines that correspond to about 1/2 the flux reported by Galas et al. Either the region observed with the FPCS is anomalously low in oxygen line emission, or the Galas et al. is too high. Galas et al. obtained their result from fits to low-resolution HEAO-1 data, and it is possible that a power-law-spectrum (which they did not investigate) may explain their data. Becker et al. and Toor have both reported successful power-law fits to the SN1006 spectrum.