4. Supernova Remnants, Soft X-ray Background

HIGH RESOLUTION SPECTROSCOPY AND PLASMA DIAGNOSTICS OF SUPERNOVA REMNANTS

Claude R. Canizares
Department of Physics and Center for Space Research
Massachusetts Institute of Technology

Abstract. The MIT group has used data from the Focal Plane Crystal Spectrometer on the *Einstein* Observatory to perform plasma diagnostics of four supernova remnants (SNRs), the Cygnus Loop, Puppis A, N132D, and Cas A. The ratio of luminosities of the forbidden line to resonance line of He-like ions of oxygen and neon allow us to show that all four SNRs depart from ionization equilibrium in that they are under-ionized for their electron temperatures. Thus despite the fact that their ages range from 300 yr to 20,000 yr, all four SNRs are still ionizing and, in that sense, are still young. We derive values of ionization time and electron temperature for one or more components in each remnant. The agreement between these values and those deduced by others using entirely different means (e.g. broad-band spectroscopy or imaging) gives us confidence in the reliability of the diagnostics. Two of the SNRs, Puppis A and N132D, show evidence for an overabundance of oxygen by factors of three or more. These results, based on a handful of weak lines, show the great promise of the much more powerful future spectroscopy missions for revealing detailed information about astrophysical plasmas.

I. INTRODUCTION

It has long been traditional to classify supernova remnants (SNRs) according to their ages, because so many of their characteristics are age-dependent. For example, in young remnants it is the shocked ejecta that dominates the emission whereas in old remnants it is the swept up interstellar medium (ISM; e.g. see Hamilton's contribution to this volume). Here I present evidence showing that in some sense *all* SNRs are young. By this I mean that the plasma that dominates the emission, whether ejecta or ISM, is still ionizing and has not reached ionization equilibrium. This idea goes back to Gorenstein, Harnden, and Tucker (1974), Itoh (1977), and others, but the strongest evidence comes from detailed plasma diagnostics of the kind I describe here.

I present results from four SNRs in order of seniority: the Cygnus Loop, Puppis A, N132D and Cas A. All the data come from the Focal Plane Crystal Spectrometer (FPCS) on the *Einstein* Observatory (Giacconi *et al.* 1979). The high spectral resolution of this instrument allowed us, for the first time, to resolve individual emission lines from other lines and from the continuum.

II. HE-LIKE TRIPLETS AS DIAGNOSTICS OF DISEQUILIBRIUM

Before presenting the data, I will review briefly the use of the relative strengths of lines from He-like ions as diagnostics of departures from ionization equilibrium (see also Dr. Mason's contribution to this meeting). The first excited state of He-like ions can be either a singlet (1s2p ^{1}P) or triplet (1s2p ^{3}P or 1s2s ^{3}S), whereas the ground state is a singlet ($1s^2\ ^1S$) (see for example Gabriel and Jordan 1969, Mewe and Schrijver 1978). Decays from the triplet excited state to the singlet ground state are second order transitions and are therefore slower than those from the singlet state, but in plasma at the low densities of SNRs they do eventually occur, giving rise to the forbidden line (from the ^3S state) and the intercombination line (from the ^3P state). Therefore, the relative strengths of these lines compared to that of the resonance line (from the permitted transition between the excited and ground singlet states) depends on the relative populations of the excited states.

For a plasma in ionization equilibrium, the excited states are populated by collisional excitation and by cascades following radiative recombination of the H-like ions. Collisions preferentially populate the singlet state whereas recombination preferentially populates the triplet states (because of their larger statistical weights). This gives rise to line ratios that are somewhat temperature sensitive (e.g. Pradhan 1983). In a plasma that is still ionizing, in other words one that is under-ionized for its electron temperature, the recombination rate is suppressed. This reduces the strengths of the forbidden and intercombination lines relative to the resonance line, giving us the desired diagnostic. The opposite case of an over-ionized, recombining plasma in which the forbidden line is enhanced has been observed in a laboratory plasma (Kallne *et al.* 1984). This case might be of interest in future studies of stellar flares, for example.

We have computed the expected line ratios as functions of electron temperature and ionization time using the non-equilibrium ionization code of Jack Hughes (Hughes and Helfand 1985) and also using our own calculation of the ionization fractions based on the data of Mewe, Gronenschild, and van den Oord (1985 and references therein) and the collision strengths for the He-like ions of Pradhan (1983 and references therein). Both these computations assume that the electrons are instantaneously heated to the given temperature. The ionization time τ is the product of electron density n_e and time t -- it is proportional to the number of electron collisions which governs the ionization, excitation and recombination processes. Comparing the measured line ratios to the calculated line ratios allows us to constrain the electron temperature T_e and τ. This assumes that the observations correspond to a reasonably homogeneous, isothermal region in the source, an assumption that I will explore further below. In some cases we have also used the computations of Hamilton, Sarazin and Chevalier (1983), which are for an inhomogeneous plasma whose emission measure distribution follows that expected for a plasma heated by an adiabatic Sedov blast wave. Hamilton and Sarazin (1984) have shown that with a modest rescaling of the parameters, these same computations are also valid for a variety of other SNR models (e.g., a reverse shock in the ejecta).

Recently Gabriel *et al.* (1988) have raised the concern that non-Maxwellian electron distributions could affect the relative ratios of the He-like triplet and disrupt the diagnostic. This is because very energetic electrons will preferentially excite the singlet state, resulting in a stronger resonance-to-forbidden line ratio even if the plasma is in ionization equilibrium. This is a serious objection but, as I will describe in more detail below, it is possible to test for the presence of such supra-thermal electrons. The consistency between our diagnostics and other determinations of the plasma parameters argues against the importance of this effect.

III. THE CYGNUS LOOP

The Cygnus Loop is a rather old remnant, with an estimated age of ~20,000 yr. and a radius of ~20pc at an assumed distance of 700 pc (Ku *et al.* 1984). The X-ray image shows a nearly circular limb-brightened shell that is several degrees across. We made a series of observations with the FPCS of a 3x30 arc min portion of a bright region in the north (see Vedder *et al.* 1986). Because of the limited surface brightness of this large diffuse source, we were only able to study three line complexes, the O VII and Ne IX triplets near 570 and 920 eV, respectively, and the O VIII Lyα and O VII 3p-1s lines around 650 eV (see Figure 1). However, even these few lines are sufficient to draw some interesting conclusions about the condition of the source. In particular, Figure 1 shows that the O VII forbidden line is much weaker than the resonance line. This is qualitatively what we expect for an under-ionized plasma.

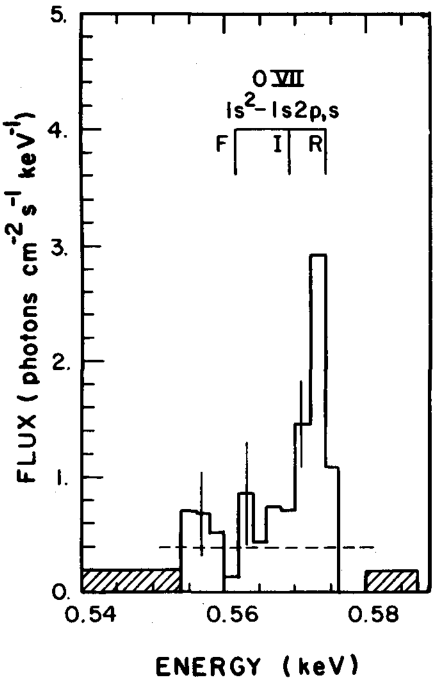
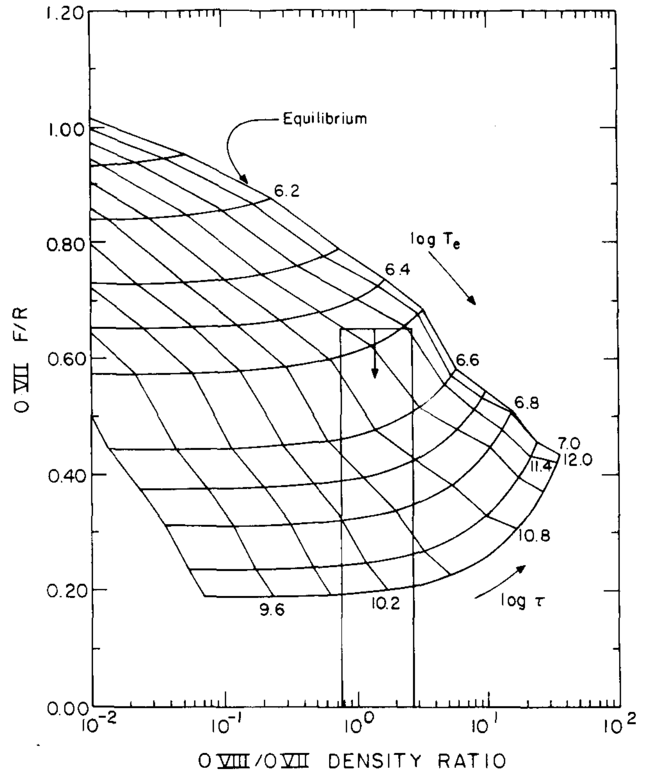


Figure 1. The He-like triplet of O VII from a portion of the Cygnus Loop as observed with the Einstein FPCS (from Vedder et al. 1986). The dashed line shows the level of the non-X-ray background (measured simultaneously in the FPCS imaging detector). The hatched regions of the spectrum were not observed. The energies of the forbidden (F), intercombination (I), and resonance (R) lines are indicated.

Figure 2 shows a plot of the forbidden-to-resonance line ratio vs. the O VIII to O VII density ratio. The grid comes from our computations. It shows the locus of models of impulsively heated plasma at various temperatures as a function of ionization time τ. The rectangle shows the three-sigma confidence region from the data of Figure 1 (the O VIII to O VII density ratio can be deduced from the ratio of the Lα line to the 3p-2s line around 650 eV). It is clear that ionization equilibrium, which corresponds to the upper right hand edge of the grid, is ruled out by the data. Formally we obtain $T_e > 3x10^6$ K and 3,000 < τ < 10,000 yr. cm^{-3}. These values are consistent with those obtained using the grids of Hamilton, Sarazin and Chevalier (1983) for inhomogeneous plasma, so they are relatively model-independent.

Ku *et al.* (1984) used the continuum shape to measure a temperature of 3x10^6 K, just the value of our lower limit, and they deduced the age to be 18,000 yr. If we adopt their temperature, we find 4,000 < τ < 8,000 yr. cm^{-3}. With their age, this implies that the electron density n_e ~ 0.2 to 0.5 cm^{-3}, which is reasonably consistent with their estimate from the surface brightness of 0.65 cm^{-3}. Tsunemi *et al.* (1988) require a non-equilibrium model with two temperature components to fit the 0.1 - 3 keV spectrum from TENMA and a rocket flight. The parameters of their low temperature component are very similar to those just quoted. The high temperature (~8x10^6 K) component would not contribute to

the O VII line flux. Furthermore, it is thought to come primarily from the interior of the Loop, outside our aperture.



The consistency of our line diagnostics with analyses of broadband spectral and imaging data gives us confidence in the reliability of our conclusion, namely that even this rather aged remnant is in a youthful state of ionization.

Figure 2. A diagnostic grid of T_e and τ in terms of observed line ratios (see text). The rectangle shows the region allowed by the observations of the Cygnus Loop (three-sigma; see Vedder et al. 1986).

IV. PUPPIS A

Puppis A is between four and five times younger than the Cygnus Loop; its age is estimated to be ~4000 yr. (Winkler, Tuttle and Kirshner 1988). Puppis A is the brightest X-ray line source in the sky after the sun, and it was the object we studied most carefully with the FPCS. The locations of our aperture during the observations roughly correspond to the interior, the sharp shock front along the northeast, and a bright region in the east that is thought to be a shocked interstellar cloud (see Petre *et al.* 1981). Much of our data on Puppis A is already in the literature, but some of it is now being studied by Kathryn Fischbach and others in our group (e.g. see the contribution of Fischbach *et al.* to this meeting). Here I will focus on the question of ionization equilibrium as indicated by the relative strengths of the He-like triplet.

As in the Cygnus Loop, the spectra of Puppis A from all three regions show the large resonance-to-forbidden line ratios indicative of non-equilibrium ionization (e.g. see Figure 3). In the case of the interior of Puppis A, we can compare our line strengths not only to the models but also to those seen in the solar corona. This is because the other oxygen line ratios are very similar in the two -- thus if Puppis A were at equilibrium it would have a temperature similar to that of the quiet corona (2-3x10^6 K; Winkler *et al.*

1981a, 1981b, Canizares and Winkler 1981, Canizares *et al.* 1983). However, in the equilibrated corona the forbidden and resonance lines of O VII are nearly equal in strength, whereas in Puppis A their ratio is ~0.3.

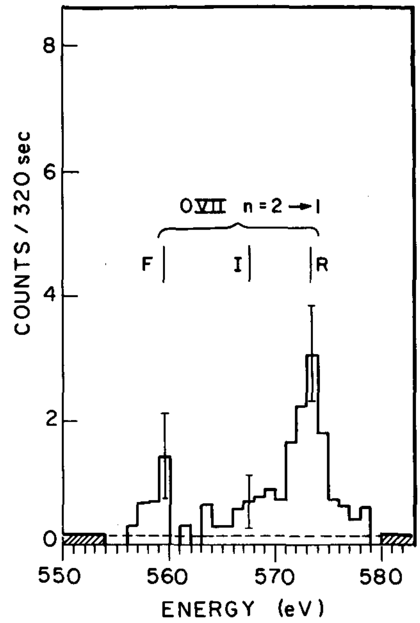


Figure 3. The He-like triplet of O VII from the interior of Puppis A as observed with the Einstein FPCS (from Winkler et al. 1981). See caption to Figure 1 for details.

Fischbach *et al.* (this volume) derive values of τ for the three regions of Puppis A using several line ratios, including the He-like triplet (see their Table 1). The results give a plausible scenario for the remnant: the interior emission comes predominantly from older plasma with densities of 0.1-0.6 cm^{-3}, the shock front is much younger and roughly an order of magnitude denser, and the bright eastern knot is comparably young but still denser by a factor of three or more.

We also have an independent consistency check on the validity of the He-like triplet diagnostic. For the interior of Puppis A, the O VIII Lα to Lβ line ratio taken together with two ratios of O VII to O VIII lines rule out ionization equilibrium without reference to the He-like triplet. This is shown in Figure 2b of Fischbach *et al.* (in this plot equilibrium corresponds to the region of τ vs. T_e space in which the dashed curves become horizontal). These results only depend on oxygen lines, so they are independent of any assumptions about relative elemental abundances.

This consistency between the He-like triplet diagnostic and the other line ratios implies that the forbidden-to-resonance line ratios are not strongly affected by suprathermal electrons (see Section II). A further argument against suprathermals comes from the broad-band spectrum of Puppis A. If several percent of the electrons in Puppis A had characteristic energies of 15 - 20 keV, which is what would be needed to affect significantly the He-like triplet (Gabriel *et al.* 1988), then they will emit *bremsstrahlung* and give rise to a high energy tail. I believe that such a tail would have been detected by experiments such as Ariel V (Zarnecki *et al.* 1978), and probably EXOSAT, TENMA and GINGA can set even tighter limits.

One further concern about our diagnostics comes from the implicit assumption that the material is reasonably homogeneous within each of the three regions. The fact that the deduced densities for the interior, shock front and eastern knot are qualitatively consistent with what one gets from the imaging analysis and the kinematic ages of the various regions implies that inhomogeneities are not grossly distorting our results. However, Jansen (1988) and colleagues have recently analyzed EXOSAT images showing considerable inhomogeneity throughout Puppis A. We are now trying to incorporate these results into our analysis.

Before leaving Puppis A, I will briefly mention the question of the relative elemental abundances in the remnant. Abundances are of great astrophysical importance. To a large extent, the detailed plasma diagnostics of things like ionization equilibrium are useful because they permit us to address such important questions. The spectrum of Puppis A shows much stronger oxygen and neon lines relative to those of Fe XVII than does the spectrum of the solar corona. In our initial analysis of the Puppis A interior, Frank Winkler and I concluded that oxygen and neon were overabundant relative to iron by factors of 3-5 compared to solar values (Canizares and Winkler 1981). Our more recent conclusion regarding the departure from ionization equilibrium opens the possibility that the apparent weakness of the Fe lines are an artifact of disequilibrium -- that the lines are weak because iron is spread among more ionization stages in Puppis A than in the sun (see also Canizares *et al.* 1983, Szymkowiak 1985). We have performed a preliminary analysis of this by setting limits on the strengths of lines of Fe XVIII and Fe XX. Our conclusion so far is that non-equilibrium effects cannot explain the entire effect, so that Puppis A does indeed contain a significant overabundance of oxygen and neon, although possibly by less than we had originally thought.

Two other observations of Puppis A in different wavebands are also relevant. Winkler, Tuttle and Kirshner (1988) discovered some optically emitting filaments that appear to be almost pure oxygen -- these show very strong O I, O II and O III lines together with Ne III, but no hydrogen lines! These filaments contain only a tiny fraction of the mass which we observe in the X-ray band, but they certainly support the conclusion that the ejecta are enriched with oxygen. The second relevant observation addresses an alternative explanation for our observed relative overabundance of oxygen to Fe, namely that the Fe is trapped in grains (see Canizares and Winkler 1981, where we argued against this possibility on theoretical grounds). Dwek *et al.* (1987) have analyzed the far infrared data on Puppis A from the IRAS satellite. The ratio of IR to X-ray luminosity is an order of magnitude less than what one would expect if the SNR contained significant amounts of dust, so depletion of iron cannot be a significant effect.

We still feel justified, therefore, in calling Puppis A the oxygen-rich remnant of a Type II supernova in a massive star.

V. N132D

N132D is also a remnant that shows optically emitting filaments that appear to be nearly pure oxygen. It is in the Large Magellanic Cloud, at a distance of about 50 kpc, and its age is roughly a thousand years, making it four times younger than Puppis A (e.g. see Hughes 1987).

We observed several portions of the spectrum of N132D (e.g. see Canizares *et al.* 1983). The most striking result is the great strength of the oxygen lines -- even more extreme than in Puppis A. Nearly 15% of the X-ray luminosity of the remnant is in the single Lα line of O VIII. In fact, the half-dozen lines that we studied account for nearly 30% of the total luminosity even though they represent only a few tiny slices of the spectrum.

Unfortunately, we have no useful results on the O VII triplet. We did measure the Ne IX forbidden to resonance line ratio, but it does not provide much of a constraint on the ionization time. Our measurements are even consistent with the remnant being at equilibrium. Taken together with the broad-band temperature measured by Hughes (1987), our line ratios give $\tau > 2500$ yr. cm^{-3}. With an age of 1300 yr. (Lasker 1980) this means that $n_e > 2$ cm^{-3}. A value of $n_e \sim 2$ cm^{-3} would be quite consistent with Hughes' value from the imaging analysis.

It is hard to avoid the conclusion that the oxygen abundance is very much enhanced in N132D. The region around 820 eV (15 A) contains three lines of Fe XVII flanked by the O VIII Lγ and Lδ lines (see Figure 4). In the solar corona, and even in Puppis A, the Fe lines are much stronger than the oxygen lines, whereas in N132D the Fe lines are barely detectable and may even be absent. When we use the line ratio grids of Hamilton, Sarazin and Chevalier (1983) for inhomogeneous, non-equilibrium models we find that a large oxygen overabundance is required. If the oxygen emission comes primarily from the interior of the SNR then the overabundance there is even more extreme (see Hughes 1987).

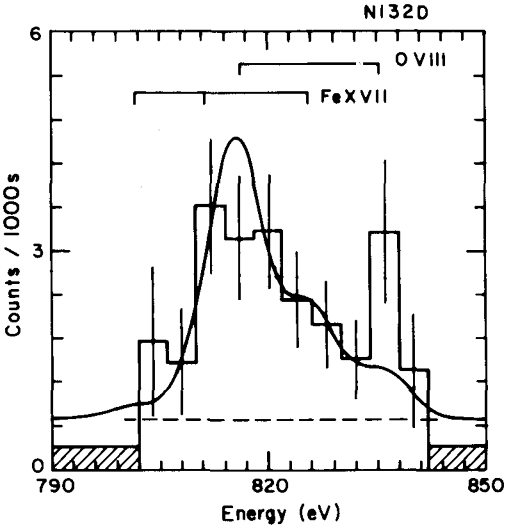


Figure 4. A portion of the spectrum of N132D as observed with the FPCS. The energies of three L lines of F XVII and of the Lβ and Lγ lines of O VIII are indicated. See caption of Figure 1 for details.

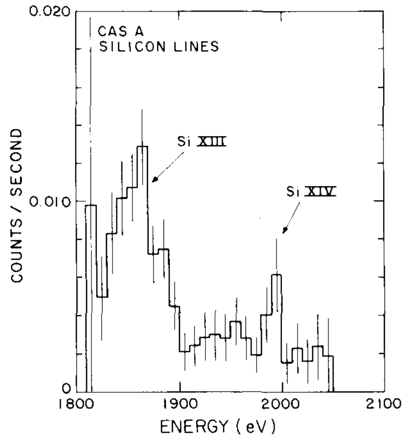


Figure 5. A portion of the spectrum of Cas A as observed with the FPCS (Markert et al., 1988). The Si XIII and XIV lines are indicated.

VI. CAS A

Cas A is yet another factor of four younger -- it's age is just over 300 years. Our observations of Cas A yielded surprising kinematic information: we measured a differential Doppler shift across the remnant indicating an asymmetric expansion velocity of ~5000 km s^{-1} (Markert *et al.* 1983). More recently, Tom Markert and Paula Blizzard have measured the strengths of the hydrogenic and He-like ions of Si, S and Ne as well as a complex of Fe L lines from 850 to 1250 keV (see Figure 5; Markert *et al.* 1988a,b).

The analysis, being performed with Jack Hughes, shows that the Si and S line ratios together map out an allowed region of T_e vs. τ parameter space. But this region of parameter space is completely incompatible with that required by the Ne lines. We believe that this apparent discrepancy is easily explained by the extreme youth of the SNR. As Andrew Hamilton has described (in this volume) young SNRs contain two distinct emission regions, one behind the primary shock in the ISM and one behind the so-called reverse shock in the expanding stellar ejecta. Our results indicate that the Si and S lines are produced primarily in the hotter ISM while the Ne lines come from the ejecta.

The broadband spectra of Tsunemi *et al.* (1986) from TENMA fit this hypothesis, as do the more recent results from EXOSAT (Jansen *et al.* 1988). The non-equilibrium analysis of Tsunemi finds a value of $T_e = 4 \times 10^7$ K and $\tau = 1500 - 4500$ yr. cm^{-3}, which falls right on the region of parameter space required by the Si and S lines. If we adopt their temperature, our lines constrain the ionization time to be $\tau \sim 2400$ yr. cm^{-3}, giving a pre-shock density of $n_o = 2.0 \pm 0.3$ cm^{-3}, which is quite reasonable for the ISM. We can then deduce the temperature and density of the shocked ejecta by assuming it is in pressure equilibrium with the shocked ISM and that its values of τ and T_e must fall in the region required by the Ne lines. We derive $T_e \sim 2.5 \times 10^6$ K and $n_o \sim 25$ cm^{-3}. These values are also very reasonable. Jansen *et al.* (1988) find a higher temperature for the cooler component, but the discrepancy could easily be due to their assumption of ionization equilibrium.

Of course, the values we deduce are only mean values (weighted by the emission measure), as the imaging analysis of Fabian *et al.* (1980) shows significant variation in the density of the ejecta on the scale of tens of arc seconds. On the other hand, since our values of the density derived from the ionization time (which is linear in density) roughly agree with his based on surface brightness (which depends on the density squared), clumping on very small scales is probably not important. This means that the mass determinations based on the imaging analysis are reasonably correct.

VII. CONCLUSION

I believe that these results demonstrate the great power of plasma diagnostics to reveal the physical conditions of optically thin sources such as SNRs. Even the measurement of only a few well-chosen lines can give remarkably precise information. In each case our deduced parameters agree with those determined by entirely different means, such as broad-band spectral fits or imaging analyses. The diagnostics are also quite model dependent: although I had insufficient time to show this, in most cases the parameters we deduce from our simple homogeneous, single-temperature models are close to those which we derive using the grids of Hamilton, Sarazin and Chevalier (1983) for an inhomogeneous Sedov blast wave.

Therefore, we are now confident in concluding that all four of the SNRs described here are still young, in the sense that they are all still ionizing, despite the fact that they range in age from 300 yr. to ~20,000 yr. Furthermore, our improved understanding of the physical conditions in the plasma gives us greater assurance in our abundance determinations. In particular, we see clear evidence for large oxygen enhancements in Puppis A and N132D.

In some ways these results only serve to whet our appetites. The FPCS was limited in sensitivity and *Einstein* had only a short (albeit happy) life. Future missions will have up to a thousandfold improvement in sensitivity for high resolution spectroscopy, and they will have extended lifetimes that will permit long range observing programs. There is little doubt that they will provide a vast new arena for detailed astrophysical studies.

REFERENCES

Canizares, C.R. and Winkler, P.F. 1981, *Ap. J.*, **246**, L33.
Canizares, C.R., Winkler, P. F., Markert, T. H., and Berg, C. 1983, in Danziger, J. and Gorenstein, P. (eds), *Supernova Remnants and Their X-ray Emission*, (Reidel), 205.
Dwek, E., Petre, R., Szymkowiak, A., and Rice, W. L. 1987, *Ap. J.*, **320**, 27.
Fabian, A. C., Willingale, R., Pye, J. P., Murray, S. S., and Fabbiano, G. 1980, *M. N. R. A. S.*, **193**, 175.
Gabriel, A., Bely-Dubau, F., Faucher, P., and Acton, L. 1988, *Ap. J.* (in press).
Gabriel, A. and Jordan, C. 1969, *M.N.R.A.S.*, **145**, 241.
Giacconi, R. 1979, *Ap. J.*, **230**, 540.
Gorenstein, P., Harnden, R., and Tucker, W. 1974, *Ap. J.*, **192**, 661.
Hamilton, A. and Sarazin, C. 1984, *Ap. J.*, **284**, 60.
Hamilton, A., Sarazin, C., and Chevalier, R. 1983, *Ap. J. Supp.*, **51**, 115.
Hughes, J. 1987, *Ap. J.*, **314**, 103.
Hughes, J. and Helfand, D. 1985, *Ap. J.*, **291**, 544.
Itoh, H., 1977, *Pub. Astron. Soc. Japan*, **29**, 813.
Jansen, F. 1988, *Ph.D. Thesis*, Leiden State University, The Netherlands.
Jansen, F., Smith, A., Bleeker, J. A. M., de Korte, P. A. J., Peacock, A., and White, N. E. 1988, *Ap. J.*, **331**, 949.
Kallne, E. *et al.* 1984, *Phys. Rev. Lett.*, **52**, 2245.
Lasker, B. 1980, *Ap. J.*, **237**, 765.
Markert, T.H., Canizares, C.R., Clark, G.W., and Winkler, P.F. 1983, *Ap. J.*, **268**, 134.
Markert T., Blizzard, P., Canizares, C., and Hughes, J. 1988a, in Roger, R. S. and Landecker, T. L. (eds) *Supernova Remnants and the Interstellar Medium*, (Cambridge Univ. Press), 129.
Markert T., Blizzard, P., Canizares, C., and Hughes, J. 1988b, in preparation.
Mewe, R., Gronenschild, E. H. B. M., and van den Oord, G. H. J. 1985, *Astron. Ap. Supp.*, **62**, 197.
Mewe, R. and Schrijver J. 1978, *Astron. Ap.*, **65**, 99.
Prahdan, A. 1983, *Phys. Rev. A.*, **28**, 2128.
Petre, R., Canizares, C.R., Kriss, G.A., and Winkler, P.F. 1981, *Ap. J.*, **258**, 22.
Szymkowiak, A. E. 1985, *NASA Tech. Memorandum 86169*.
Tsunemi, H., Manabe, M., Yamashita, K., and Koyama, K. 1988, *Publ. Astron. Soc. Japan*, **40**, 449.
Winkler, P.F. Canizares, C.R., Clark, G.W., Markert, T.H., and Petre, R. 1981, *Ap. J.*, **245**, 574.
Winkler, P.F., Tuttle, J.H., Kirshner, R.P. and Irwin, M.J. 1988, in *Supernova Remnants and the Interstellar Medium*, eds. R.S. Roger and T.L. Landecker, (Cambridge University Press, Cambridge 65.)
Zarnecki, J. C., Culhane, J. J., Toor, A., Seward, F. D., and Charles, P. A. 1978, *Ap. J. (Letters)*, **219**, L17.

ACKNOWLEDGEMENTS. I thank many colleagues whose work in progress I have quoted here. In particular I am grateful to Leah Bateman, Paula Blizzard, Kathryn Fischbach, Jack Hughes, Tom Markert, Tim Pfafman, Atul Pradhan, Pablo Saez, and Peter Vedder. I thank Fred Jansen for showing us his work prior to publication, and Elaine Aufiero for her expert preparation of the manuscript.

DISCUSSION-C. Canizares

J. Schmitt: In the case of stellar coronae, one worries very much about multi-thermal plasmas. You don't seem to worry about this much. Can you explain why?

C. Canizares: We do worry about multi-thermal plasmas, but at this stage there is only a limited amount we can do about them. When their effects are large, as in Cas A, we can actually distinguish two components. In most cases, we must make some simplifying assumption, such as adopting an isothermal or Sedov model. Happily, some of the astrophysically important conclusions that we draw are not too dependent on these assumptions, as is shown by the results of Hamilton and Sarazin (1984) and the apparent insensitivity of our conclusions to the model chosen.

P. Winkler: Does your analysis shed any light on the question of post-shock equilibration between ion and electron temperatures – which remains a major source of uncertainty in understanding SNR plasmas?

C. Canizares: Not really. All the results I have quoted assume $T_e = T_i$, which is at least plausible. It is possible that in some cases we will be able to rule out the extreme case of no energy transfer between protons and electrons as requiring implausible parameters (e.g. see Jansen *et al.* 1988), but modest departures from equality will probably be very difficult to discern. In the future, when we have better diagnostics for T_e, we may be able to answer this question.