X-RAY SPECTROSCOPIC MEASUREMENTS OF NON-EQUILIBRIUM IONIZATION IN SUPERNOVA REMNANTS

T. H. Markert, C. R. Canizares, T. Pfafman and P. Vedder
MIT, Center for Space Research, Cambridge, MA 02139

P. F. Winkler
Dept. of Physics, Middlebury College, Middlebury, VT 05753

A. Pradhan
JILA, University of Colorado, Boulder, CO 80309

INTRODUCTION

When a cool plasma is shock-heated to X-ray temperatures, the ionization structure does not attain its final, equilibrium value immmediately, but proceeds toward it through electron-ion collisions with a timescale $\tau \equiv n_e t$ of order 10^{12} cm^{-3} sec. For supernova remnants (SNRs), where $0.1 \lesssim n_e \lesssim 10$ cm^{-3} typically, the time required to achieve collisional ionization equilibrium (CIE) can be greater than the age of the remnant. Even if the SNR is quite old, that part of the remnant which is emitting most of the X-rays may have been shocked relatively recently, so that the assumption of CIE may be inappropriate (see below).

The question of ionization equilibrium is of great astrophysical importance in the study of SNRs because it affects the deduced values of their masses and elemental abundances (e.g. Shull 1982). Mass determinations are affected because underionized plasma generally has a much higher emissivity in soft X-rays than equilibrium plasma. Unless this is accounted for, the deduced value of the density and therefore of the mass, will be considerably overestimated.

In this paper we will discuss a simple model for non-equilibrium ionization (NEI) that we have used to assist us in the analysis of high-resolution ($E/\Delta E \sim 50$ to 500) X-ray spectra obtained with the Focal Plane Crystal Spectrometer (FPCS) on the Einstein Observatory (Giacconi et al. 1979). Here we will apply this model to FPCS observations of 3 SNRs.

MODEL

We begin with a relatively cool plasma with cosmic abundances and shock-heat it to X-ray temperatures (i.e. we assign a value to the electron temperature T_e between 10^6 and several $\times 10^7$ K). The density of each ion (for a particular element) is given by

$$\frac{1}{n_e}\frac{dn_z}{dt} = n_{z-1}S_{z-1} - n_z(S_z + \alpha_z) + n_{z+1}\alpha_{z+1}$$

where z is the ionic charge, S_z is the electron collisional ionization rate for the process $n_z \rightarrow n_{z+1}$ and α_z is the total (radiative plus dielectronic) recombination rate for $n_z \rightarrow n_{z-1}$. These coefficients were taken from Mewe and Schrijver (1978) except for the case of iron, where they were taken from Jacobs et al. (1977).

These ion balance equations were solved on the computer by a modified Euler's method and provide us with the ion structure of each element as a function of τ. An example appears in Figure 1.

Some of the most useful diagnostics for the determination of NEI parameters are the relative intensities of the lines of the n = 2 to n = 1 transitions of the helium-like ions (e.g. Pradhan and Shull 1981). We computed the ratios of the intensities of these lines in the low-density limit including the effects of electron impact excitation, inner-shell ionization of the Li-like ion, radiative and dielectronic recombination, and cascades. (The rate coefficients were determined by one of us [A.P.].)

When the ionization balance and relative line strengths for the helium-like ions have been determined for a set of τ and T_e, we prepared a set of graphs with line and ion ratios on the axes and an overlaid τ - T_e grid. Figure 2 is an illustration of the final output for a set of oxygen lines. In order to use these graphs we must have a measurement of the He-like lines and an estimate of the H to He-like ion population ratio for the element in question. This latter ratio can be obtained from any two lines of the same species for which electron impact is the dominant excitation mechanism. For the example in Figure 2 we selected the O VIII Ly α (n = 2 to n = 1) and the O VII He β lines (n = 3 to n = 1) at 654 and 666 eV respectively.

Once the set of ratios is determined and plotted, a corresponding range of τ and T_e is determined from the grid. In the example (Figure 2) we have used observations taken from the interior of Puppis A (Winkler et al. 1981) to find $\tau \sim 2.2 \times 10^{10}$ cm^{-3} s and $T_e \sim 6 \times 10^6$ K. Note that this plasma is well separated from CIE, which is represented by the log τ = 12.0 line. Also note that the temperature determined exclusively from the ion population ratio (assuming CIE) is log $T_e \sim 6.4$, much cooler than found by our NEI model (log $T_e \sim 6.8$). This indicates that the plasma is still ionizing and the H to He-like ratio is smaller than would be expected for a plasma in equilibrium at log $T_e \sim 6.8$.

EXAMPLES

We have applied our model to several SNRs and here present some of the results. All data were obtained with the FPCS.

A. Puppis A Knot

The highest X-ray surface brightness in Puppis A (as measured by the Einstein HRI) is from a knot of emission which lies just to the east of the Puppis A shock front (Petre et al. 1982). We have FPCS measurements of this knot for the He-like neon lines (He α n = 2 to n = 1 and Heβ n = 3 to n = 1) and H-like Lyman α, so that we are able to restrict the τ - T_e region. Furthermore, we have determined the H-like to He-like oxygen population ratio from the O VIII Ly α and O VII He β line strengths, and so can further restrict the allowed region of (τ, T_e) space. We find $T_e = (7 \pm 1) \times 10^6$ K and $\tau = (3 \pm 0.6) \times 10^{10}$ cm^{-3} s. (Note that our results are independent of the relative abundances of oxygen to neon).

Petre et al. (1982) interpreted the eastern knot to be a recently shocked interstellar cloud with electron density $n_e \sim 10$ cm^{-3}. Our value of $\tau \simeq n_e \times t$ implies that the shock occurred approximately 3×10^9 s = 100 yr ago. The electron temperature implies a shock velocity of $\simeq 700$ km s^{-1} (assuming electron-ion equipartition)). In 100 years the shock would thus traverse ~ 0.1 pc, about the size of the bright features in the knot.

B. Cygnus Loop

We scanned an X-ray bright region in the NW of the Cygnus Loop with the FPCS. We observed the O VII He α and He β lines, the O VIII Ly α line and the Ne IX He α lines, enabling us to restrict the values of τ and T_e. We find $7.0 > \log T_e > 6.45$ and $9.9 < \log \tau < 11.4$, significantly far from CIE. Although the Cygnus Loop is $\sim$ 20,000 yr. old (Ku et al. 1984), it is not necessary to require CIE. The observed X-ray emission may rise from a more recently shocked region. Even if the plasma was shocked 20,000 yr. ago, our results require only $n_e \lesssim 0.47$ cm^{-3}. Ku et al. (1984) find the mean density of the interstellar medium to be ~ 0.16 cm^{-3} or, assuming a hard shock $\langle n_e \rangle \sim 0.64$ cm^{-3}, not far from what we require.

C. N132D

N132D is a relatively young (age estimates range from 1000 to 3000 years) remnant of a Type II supernova in the Large Magellanic Cloud. Our observations of Ne IX He α and Ne X Ly α lines are sufficient to restrict (τ, T_e) space to a region centered about $\log \tau = 11.4$ and $\log T_e = 6.8$. Unlike our results for Puppis A and the Cygnus Loop, CIE is permitted for N132D, for temperatures between $6.65 \lesssim \log T_e \lesssim 6.80$. If N132D has attained CIE, then the mean n_e must be $\gtrsim 10$ cm^{-3} (this is the mean density for the entire remnant, since N132D fits within the FPCS viewing aperture). Such a density would be extremely high if we were viewing primarily the shocked interstellar medium. However, other FPCS observations of this object require a large overabundance of oxygen relative to iron, suggesting that most of the X-ray emission comes from the supernova ejecta, for which the oxygen has been greatly enriched by the Type II supernova explosion. The density of the ejecta can be considerably higher than the ambient medium and CIE could be attained in a few thousand years.

COMPARISON WITH OTHER MODELS

Our model provides a simple, but fairly accurate picture of several astrophysical situations. For SNRs, it is certainly appropriate for observations of recently shocked interstellar clouds (such as the knot in Puppis A) or a relatively small portion of a very extended object (such as the FPCS observations of the Cygnus Loop). In fact, it can be used for any situation where the plasma can be characterized by a single electron temperature and ionization time. Even in more complex situations, such as for N132D where there is a superposition of plasmas shocked over a long period of time at different temperatures, the X-ray spectrum is frequently dominated by plasma with a small range of T_e and τ. Hamilton and Sarazin (1984) have shown this to be true for a wide range of SNR models. We have recently begun to compare our model with the more complex Sedov model developed by Hamilton, Sarazin and Chevalier (1983). We find considerable agreement between the two pictures if we interpret our T_e and τ as the mean electron temperature and ionization time of the material in the primary shock.

This work was supported in part by NASA Contract NAS-8-30752.

REFERENCES

Giacconi, R. et al. 1979, Astrophys. J., 230, 540.

Hamilton, A. J. S., Sarazin, C. L., and Chevalier, R. A. 1983, Astrophys. J. (Suppl.), 51, 115.

Hamilton A. J. S. and Sarazin, C. L., 1984, submitted to Astrophys. J.

Jacobs, V. L., Davis, J., Kepple, P. C. and Blaha, M. 1977, Astrophys. J., 211, 605.

Ku, W. H-M., Kahn, S. M., Pisarski, R. and Long, K. S. 1984, Astrophys. J., 278, 615.

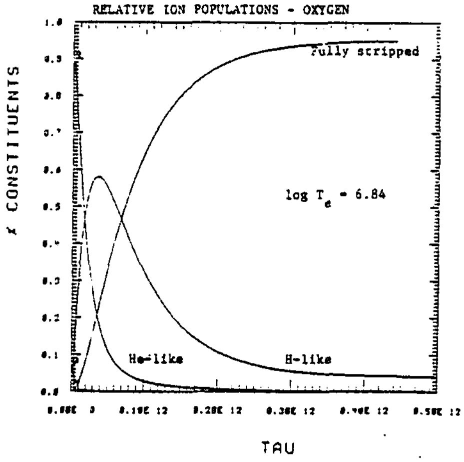
Mewe, R. and Schrijver, J. 1978, Astron. Astrophys., 65, 99.

Petre, R., Canizares, C. R., Kriss, G. A. and Winkler, P. F. 1982, Astrophys. J., 258, 22.

Pradhan, A. K. and Shull, J. M. 1982, Astrophys. J., 249, 821.

Shull, J. M. 1982, Astrophys. J., 262, 308.

Winkler, P. F., Canizares, C. R., Clark, G. W., Markert, T. H. and Petre, P. F. 1981, Astrophys. J., 245, 574.



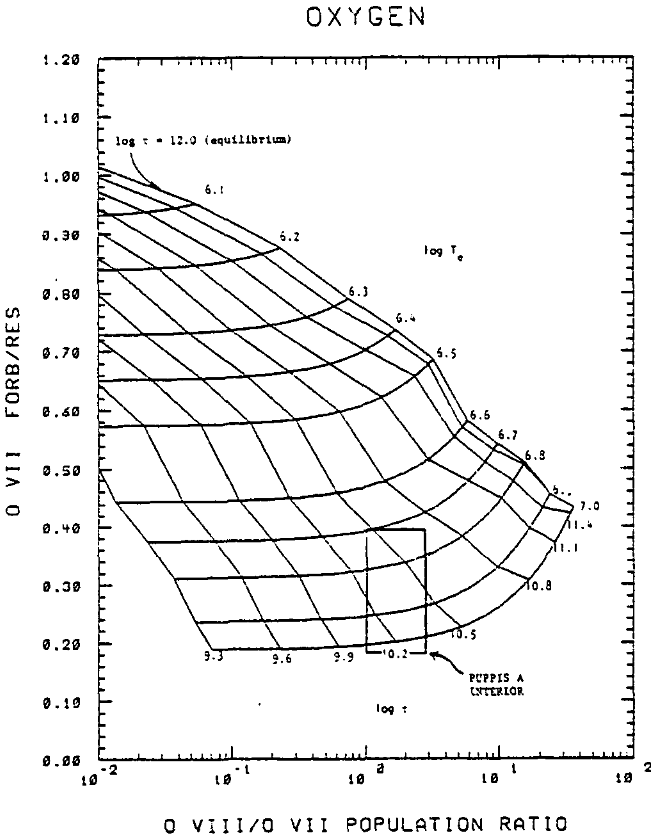


Fig. 1 (above) Solution to ionization balance equations for an oxygen plasma suddenly heated to log T_e = 6.84. Note that CIE is essentially established by $\tau = 3\times10^{11}$.
Fig. 2 (right) Determination of NEI parameters (T_e,τ) from observations of oxygen lines. The example is from FPCS observations of Puppis A.