THE INTERSTELLAR MEDIUM IN THE LINE OF SIGHT TO X PERSEI AND 3U 0352 +30

K. O. Mason, N. E. White, P. W. Sanford and F. J. Hawkins

Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey

and

J. F. Drake and D. G. York

Princeton University Observatory, Princeton, New Jersey, USA

(Received 1976 January 23; in original form 1975 September 19)

SUMMARY

The X-ray absorption column of 3U 0352 +30 derived with the Copernicus X-ray telescopes is compared with (a) the atomic and molecular hydrogen column densities in the line of sight to the star X Per, as measured with the Copernicus ultraviolet telescopes, and (b) the visible reddening of X Per, by means of the reddening/X-ray absorption column relationships derived by Ryter, Cesarsky & Audouze and Gorenstein.

The results are consistent with both star and X-ray source being equidistant. When comparing X-ray absorbing column densities with those derived by other means, we find that it is necessary to include the effects of molecular hydrogen in the line of sight to X Per and, in particular, the related number of medium-weight elements. We suggest that the failure to do this in previous work may account for reported discrepancies between the X-ray and radio column densities to the Crab Nebula and other sources, as first suggested by Margon. The far-ultraviolet extinction curve of X Per is presented.

I. INTRODUCTION

On the basis of positional coincidence the peculiar 6 mag Be star X Per is a candidate for identification with the X-ray source 3U 0352 +30 (Braes & Miley 1972; Brucato & Kristian 1972; van den Bergh 1972). The common area between the two independent X-ray position determinations of Giacconi et al. (1974) and Hawkins, Mason & Sanford (1975) is 7 (arcmin)². X Per was observed for two days in 1972 December by the Copernicus satellite. The Princeton ultraviolet spectrometer scanned the spectrum of the star in the wavelength range 1000–1260 Å while the MSSL X-ray telescopes simultaneously monitored the X-ray source in the energy band 0.7–7.5 keV. Here we compare the neutral atomic hydrogen and molecular hydrogen columns in the line of sight to X Per as derived from the ultraviolet spectrum, with the low-energy absorption turnover in the X-ray spectrum, and test whether these are consistent with the star and X-ray source being equidistant. The visual extinction expected in the optical candidate of 3U 0352 +30 is also calculated from the empirical relationships between X-ray absorption and colour excess, $E_{B-V}$, of Ryter, Cesarsky & Audouze (1975) and Gorenstein (1975) and is compared with the extinction observed in X Per.
The results obtained throw light on the relationship between the low-energy X-ray absorption measure, \( N_x \), and the true column density of hydrogen atoms, \( N_T \). Fritz et al. (1971), Charles, Culhane & Tuohy (1973) and others have pointed out that in the case of the Crab Nebula, a serious discrepancy exists between \( N_x \) determined from X-ray spectra and the column density determined from 21-cm absorption. There is evidence for similar effects in the cases of the Tycho supernova remnant (Coleman et al. 1973), Cygnus A (Longair & Willmore 1974) and several other low-latitude X-ray sources (Illovsy 1971). The discrepancy becomes even more severe for sources with column densities in the range \( 10^{21} \) to about \( 5 \times 10^{22} \) atom cm\(^{-2} \) when the effects of interstellar grains are included (Fireman 1974). Solutions postulating increased abundances for the heavy elements have been proposed (e.g. Fritz et al. 1971; Charles, Culhane & Tuohy 1973, see also Burginyyon, Hill & Seward 1975). Margon (1974) suggested that molecular hydrogen might increase the opacity of the interstellar medium (ISM) sufficiently to account for the discrepancy: while theoretical and experimental absorption cross-sections of the hydrogen molecule disagree by an order of magnitude (Brown & Gould 1970; Cruddace et al. 1974), we note that absorption due to the related increase of heavy elements, necessary to maintain the abundance ratios, would in any event be more significant. However, Rytter et al. (1975) and Gorenstein (1975) conclude from an empirical study of the X-ray column densities and visual reddening of several supernova remnants that the amount of molecular hydrogen in the interstellar medium as a whole is small.

It is evident, therefore, that if X Per and 3U 0352 + 30 are indeed members of the same system, a simultaneous measurement of the atomic hydrogen, molecular hydrogen and X-ray column densities would be of interest.

2. Observations

2.1 Ultraviolet

Two spectra of X Per were obtained with tube U2 at 0.2 Å resolution. Both are of relative low quality, with S/N \( \sim 10 \). In addition, the guidance was poor due to the faintness of the star and some regions of the spectrum were missed completely. However, spacecraft telemetry gives an unambiguous record of where the guidance was poor so that there is no danger of mistaking a momentary drift of the image away from the slit as a broad absorption line.

Both scans show the Ly \( \alpha \) line clearly. The line is saturated, so the residual stray light on U2 (Rogerson et al. 1973) presented no problem. The full width at half maximum, \( \lambda_F \), is related to the equivalent width, \( W_\lambda \), by the equation \( W_\lambda = 1.48 \lambda_F \) as long as the line is damped \( (N_H > 5 \times 10^{18} \text{ cm}^{-2}) \). We obtain \( W_\lambda = 8 \pm 2 \) Å, or \( N_H = (2.0 \pm 0.5) \times 10^{20} \text{ cm}^{-2} \).

The molecular hydrogen band structure is also clearly in evidence in both spectra. Of the 10 possible scans over the \((4, 0)\) to \((0, 0)\) bands of molecular hydrogen, five are not usable because of data losses resulting from poor guidance. Of those remaining, two \((0, 0)\) bands were not used, as in this case (and frequently in other stars as well) this band yields a column density which is considerably higher than, and inconsistent with, the column densities derived from the \((4, 0)\) to \((1, 0)\) bands. The profiles of the remaining three bands were fitted by computer (reproducing the continuum across the line). A damping profile was used since these lines clearly have radiation-damping wings. The result for the
column density of H\textsubscript{2} in the J = 0 level (N\textsubscript{0}) is N\textsubscript{0} = (6.0 \pm 1.5) \times 10^{20} \text{ cm}^{-2} and in the J = 1 level (N\textsubscript{1}) is N\textsubscript{1} = (5.0 \pm 1.5) \times 10^{20} \text{ cm}^{-2}. The total hydrogen column density to X Per (N\textsubscript{T} = 2N\textsubscript{H2} + N\textsubscript{H}) is then N\textsubscript{T} = (2.4 \pm 0.4) \times 10^{21} \text{ cm}^{-2} and the fraction of hydrogen in molecular form (f = 2N\textsubscript{H2}/N\textsubscript{T}) is 0.92 \pm 0.04.

2.2 X-ray

The absorption turnover in the X-ray spectrum can be expressed as

\[ S(E) = F(E) \exp\left(-\frac{E}{E_a}/E\right), \]

where \( F \) represents the intrinsic source spectrum as some function of energy, \( E \), and the exponential term represents the absorption turnover. If \( N_X \) is the equivalent column density of hydrogen atoms with an effective absorption cross-section \( \sigma(E) \), the exponent \( E_a/E \) may be replaced by \( \sigma(E) N_X \). Hydrogen itself contributes very little to the opacity of the ISM above 0.5 keV, the main absorbers being the medium-weight elements oxygen, neon, etc. The value of \( N_X \) is therefore critically dependent on the model assumed for the ISM, so we derive the absorption measure in terms of both \( E_a \) and of \( N_X \).

3U 0352 + 30 was observed with three of the four MSSL X-ray detectors, the 0.7-1.7 keV telescope, the 1.0-3.0 keV telescope and the 2.5-7.5 keV collimated proportional counter. A six-channel pulse height analyser (PHA) was connected for part of the observation to the 0.7-1.7 keV telescope, and to the 2.5-7.5 keV detector for the rest. Because of the manner in which the data were taken, it was convenient to derive the spectral parameters of the source in two ways. Firstly a two-dimensional grid was generated in spectral slope and low-energy absorption measure and each of these combinations of parameters was folded through the efficiency functions of the three detectors to determine the expected count rate. The slope and absorption measure which gave a predicted count distribution corresponding to that observed were adopted as the most likely source spectrum. The errors in these parameters correspond to the range allowed by the 2 \( \sigma \) uncertainties in the counting rates of the three detectors. Secondly, an independent estimate of the spectral parameters was made from the two sets of PHA information, in the 0.7-1.7 and 2.5-7.5 keV ranges. Again a range of trial spectra were folded through the instrumental response curves. The total predicted count in each six-channel PHA set was then normalized to the observed count (making this procedure independent of the first) and the predicted and observed energy distributions compared by means of a \( \chi^2 \) test. The spectral parameters which gave the minimum value of \( \chi^2 \) were adopted as the best-fitting source spectrum. Uncertainties in the spectral parameters were derived as described by Margon et al. (1975).

The results from the two methods agree well and are listed in Table I. A power-law spectral approximation was used throughout. During the observation an absorption event occurred giving an absorption column as high as twice that found here (White et al. 1976). In this work the data during the event are excluded.

Table I lists \( N_X \) from our data for several models of the ISM. The cross-sections of Brown & Gould (1970) have been used extensively in recent X-ray literature. Fireman (1974) has derived cross-sections which include the contributions of some additional medium-weight elements and has examined the consequences of having the medium-weight elements locked up in grains; this increases the transmission of the ISM to photons in the energy range 0.5 keV to about 2.5 keV. We have also computed \( N_X \) assuming a molecular hydrogen fraction as derived from the ultra-
TABLE I
X Per

Ultraviolet measurements
Neutral hydrogen column \( N_H = (0.2 \pm 0.05) \times 10^{21} \text{ atom cm}^{-2} \)
Molecular hydrogen column \( N_{\text{H}_2} = (1.1 \pm 0.3) \times 10^{21} \text{ atom cm}^{-2} \)
Total hydrogen column \( N_T = (2N_{\text{H}_2} + N_H) = (2.4 \pm 0.4) \times 10^{21} \text{ atom cm}^{-2} \)

Reddening
Expected column \( N_x = (3.7 \pm 1.0) \times 10^{21} \text{ atom cm}^{-2} \)
(Assumes \( E_{B-V} = 0.55 \) and \( N_x - E_{B-V} \) relation of Ryter et al. (1975) which uses Brown & Gould (1970) model for the ISM.)

\[ 3 \text{U} \, 0352 + 30 \]
Photon index

3-detector power-law fit: \( \alpha = -1.16 \pm 0.16, \quad E_a = 1.0 \pm 0.3 \text{ keV} \)
PHA power-law fit: \( \alpha = -1.2 \pm 0.3, \quad E_a = 0.8 \pm 0.5 \text{ keV} \)
Weighted mean: \( \alpha = -1.17 \pm 0.10, \quad E_a = 0.9 \pm 0.2 \text{ keV} \)

Brown & Gould (1970) model for ISM, all hydrogen atomic
\( \alpha = -1.17 \pm 0.10, \quad N_x = (4.0 \pm 1.0) \times 10^{21} \text{ atom cm}^{-2} \)

Fireman (1974) model for ISM, all hydrogen atomic
No grains \( \alpha = -1.17 \pm 0.10, \quad N_x = (3.3 \pm 1.0) \times 10^{21} \text{ atom cm}^{-2} \)
\( 0.15 \mu \text{m} \) grains \( \alpha = -1.19 \pm 0.10, \quad N_x = (3.8 \pm 1.3) \times 10^{21} \text{ atom cm}^{-2} \)
\( 0.60 \mu \text{m} \) grains \( \alpha = -1.23 \pm 0.10, \quad N_x = (5.2 \pm 1.7) \times 10^{21} \text{ atom cm}^{-2} \)

No grains \( \alpha = -1.15 \pm 0.10, \quad N_x = (2.6 \pm 0.9) \times 10^{21} \text{ atom cm}^{-2} \)
\( 0.15 \mu \text{m} \) grains \( \alpha = -1.17 \pm 0.10, \quad N_x = (2.8 \pm 1.0) \times 10^{21} \text{ atom cm}^{-2} \)
\( 0.60 \mu \text{m} \) grains \( \alpha = -1.19 \pm 0.10, \quad N_x = (3.7 \pm 1.2) \times 10^{21} \text{ atom cm}^{-2} \)

violet data and the large molecular hydrogen cross-section given by Brown & Gould (1970). This sets a maximum on the likely absorption by the molecular species itself.

3. DISCUSSION

The accuracy to which we can determine the number of hydrogen atoms in the line of sight from the X-ray spectrum is, in this case, clearly limited by our understanding of the absorbing properties of the ISM. Varying the molecular hydrogen cross-section between the value given by Crutace et al. (1974) and that of Brown & Gould (1970), and the size of interstellar grains between 0 and 0.6 (Fireman 1974), alters \( N_x \) by a factor of 2. Nor have we exhausted the possible variables; for instance, the degree of ionization of helium in the line of sight to X Per is unknown. Helium is an important source of opacity at the energies we are considering, and the cross-section of \( \text{He}^+ \) is about half that of He. Nevertheless, the derived values of \( N_x \) can usefully be compared with the \( \text{H}_2 \) and H columns.

Table I shows that \( N_x \) and \( N_T \) are consistent. \( N_x \) is perhaps slightly larger than \( N_T \) but, if the star and X-ray source belong to the same system, this might be expected since our ultraviolet observations did not determine the amount of ionized hydrogen in the line of sight. Moreover, the X-ray source may suffer some local attenuation as mentioned earlier (White et al. 1976).

The measured \( N_x \) may also be compared with that expected from the visual extinction of X Per on the assumption the latter is not anomalous. Although Blaauw (1961) points out that the visible colours of X Per (\( B-V = 0.30, \quad U-B = \))
Fig. 1. The far-ultraviolet extinction curve for X Per, normalized to $E(B-V) = 1.0$, assuming $E(B-V) = 0.55$, and comparing the observed count rates for X Per with those of the O9 IV star μ Col. The two spectra were observed with the Copernicus satellite spectrometer within one month of each other.

0.82) are peculiar compared with a normally-reddened star of the same spectral type, Moffat, Haupt & Schmidt-Kaler (1973) suggest that this peculiarity can be explained by emission at the Balmer limit as observed in their spectra. This only affects the $U$ band, so that the $B-V$ index can be used to derive the true reddening of X Per. Further they note that the reddening is likely to be primarily interstellar as distinct from circumstellar, since no infrared excess is seen for the star (Neugebauer & Leighton 1969; Cohen 1973).

The far-ultraviolet extinction curve of X Per from the Copernicus observations supports the view that the reddening of the star is normal. The extinction curve is shown in Fig. 1—assuming $E_{(B-V)} = 0.55$ (cf. Moffat et al. 1973). The slope from 8 μm$^{-1}$ to 10 μm$^{-1}$ is 2.7 ± 0.4, in agreement with the data presented by York et al. (1973) which yield a slope of 2.5 ± 0.5. This suggests that X Per is not intrinsically very red, as is often the case with Be stars, and the data are consistent with a normal mix of grains producing the far-ultraviolet and visible extinction (see, for example, Witt 1973).

We can therefore use the relationship of Ryter et al. (1975) ($N_x/E_{B-V} = (6.8 ± 1.6) \times 10^{21}$ equivalent H atoms cm$^{-2}$ mag$^{-1}$) or that of Gorenstein (1975) ($N_x/E_{B-V} = (3.5 ± 0.5) \times 10^{21}$ equivalent H atoms cm$^{-2}$ mag$^{-1}$).
\[ E_{B-V} = 6.6 \times 10^{21} \text{ equivalent H atoms cm}^{-2} \text{ mag}^{-1} \] to obtain the expected X-ray column density to X Per \((N_x)\). Using the figures of Rytter et al. we derive, for \( E_{B-V} = 0.55 \), \( N_x = (3.7 \pm 1.0) \times 10^{21} \text{ atom cm}^{-2} \), agreeing with the X-ray determination of \( N_x \) from the Brown & Gould model, which is \((4.0 \pm 1.0) \times 10^{21} \text{ atom cm}^{-2} \).

The data therefore satisfy a necessary criterion for the identification of \(3\,\mbox{U\,0352} + 30\) with X Per, that the minimum X-ray column density be consistent with the column density of interstellar material measured in the line of sight to the optical star. However, this is not sufficient evidence to demonstrate unequivocably an identification. For instance, if most of the observed absorption takes place in a molecular cloud closer to us than X Per, \(3\,\mbox{U\,0352} + 30\) \((b = -17^\circ)\) could be extragalactic and still show an absorption column consistent with that of the optical star. We regard the latter possibility as unlikely, however, in view of the short-term regular X-ray variability observed (White et al. 1976). If it is galactic, the X-ray source must be within a few kiloparsecs or else very far off the galactic plane (X Per lies at a distance of \(\sim 350\) pc according to Brucato & Kristian 1972).

At the other extreme, there is no way to determine what fraction of the X-ray absorption attributed to the ISM is actually intrinsic to \(3\,\mbox{U\,0352} + 30\). The source does suffer local attenuation, at least on occasion, since the measured absorption column is variable (White et al. 1976). If an X-ray column density were ever to be measured which was significantly below that determined from the ultraviolet observation of X Per, serious doubt would be cast on the proposed identification of the X-ray and optical star.

Lastly we note that the fraction of hydrogen in molecular form in the line of sight to X Per is \(0.92 \pm 0.04\). If \(3\,\mbox{U\,0352} + 30\) were a radio source, and assuming its association with X Per, estimates of the hydrogen column density in the line of sight based on 21-cm absorption, which is only sensitive to hydrogen in the atomic form, would be an order of magnitude lower than the observed X-ray column density. It seems natural, therefore, to explain the discrepancies mentioned earlier between the 21-cm and X-ray column density determinations in terms of molecular hydrogen. The arguments for believing that there is substantial \(\text{H}_2\) in the line of sight to the Crab have been summarized by Margon (1974), and \(\text{H}_2\) has been shown to be present in the lines of sight to virtually all stars with a colour excess \(E(B-V)\) of \(0.1\) or more (Spitzer et al. 1973). In the case of X Per/\(3\,\mbox{U\,0352} + 30\), for which comparison of the total hydrogen column density of derived from X-ray and from ultraviolet measurements is possible, agreement between the two methods occurs.

### 4. Conclusion

We have shown that the measured \(H\) and \(\text{H}_2\) columns, and the visible extinction in the line of sight to X Per are consistent with the low-energy cut-off observed in \(3\,\mbox{U\,0352} + 30\), within the uncertainties in the absorption properties of the ISM. This provides further support for the identification of \(3\,\mbox{U\,0352} + 30\) with the X Per system when taken together with their positional coincidence (Hawkins, Mason & Sanford 1975). The high molecular-hydrogen column density to X Per emphasizes the need to include molecular hydrogen and associated heavier atoms when comparing observed hydrogen column densities with those inferred from X-ray absorption. Only if the mean grain size in the ISM is large do our data require that \(\text{H}_2\) itself have a large X-ray absorption cross-section.
We have profited from helpful discussions with Bruce Margon, Philip Charles and Paul Murdin, and we are grateful to the continued support and advice of Professor R. L. F. Boyd, CBE, FRS, throughout this work. Two of us (KOM and NEW) acknowledge the financial support of the Science Research Council. JFD and DGY acknowledge support under NASA grant No. NAS 5-1810 to Princeton University.

REFERENCES