THE ASTROPHYSICAL JOURNAL 241:1148-1152, 1980 November 1

OPTICAL AND X-RAY STUDIES OF 2A 1822−371

PHILIP CHARLES[1] AND JOHN R. THORSTENSEN[1]
Space Sciences Laboratory and Department of Astronomy, University of California, Berkeley

AND

PAUL BARR
Mullard Space Science Laboratory, University College London
Received 1980 March 20; accepted 1980 April 29

ABSTRACT

Optical spectroscopy in the $\lambda\lambda$3400–5000 band of the counterpart of 2A 1822−371 obtained at CTIO is presented. This very-ultraviolet object ($V = 15.3$, $U-B = -0.9$) displays the C III/N III $\lambda\lambda$4640–4650 complex and He II λ4686, together with two broad emission features in the UV at $\lambda\lambda$3765 and 3815. We discuss the identification of these features and suggest they are due to O III and He II. Our photographic plate material enables a refinement of the Seitzer *et al.* binary period to 5.5704±0.0003 hr. The X-ray spectrum of this object obtained by *Ariel 5* is best fitted by a 2.4 keV blackbody spectrum. No evidence for binary modulation, pulsations, or bursts was found in the X-ray data.
Subject headings: stars: emission-line — stars: individual — X-rays: binaries

I. INTRODUCTION

The recent increase in the number of optically identified X-ray sources has largely been due to the substantial number of less than 1′ error boxes produced by the modulation collimator experiments on the *SAS 3* and *HEAO 1* satellites (see, e.g., the review by Bradt *et al.* 1979). However, apart from the massive primary, early-type binaries, most of the identifications indicate systems with high $L_x/L_{\rm opt}$ values ($\gtrsim 10^3$) and spectroscopic similarities to Sco X-1 (see, e.g., Cowley 1979). Only a few of the identified systems have low $L_x/L_{\rm opt}$ ratios ($\lesssim 10^2$), thereby inviting comparison with the essentially unique object Her X-1/HZ Her. These are Cyg X-2 (Cowley, Crampton, and Hutchings 1979), 4U 2129+47 (Thorstensen *et al.* 1979), and 2S 0921−630 (Li *et al.* 1978). As the result of an accurate *HEAO 1* location, Griffiths *et al.* (1978) identified 2A 1822−371 with a blue, ~16 mag star which exhibits the "classical" X-ray emission lines (C III/N III $\lambda\lambda$4640–4650; He II λ4686) and a large UV excess. It has an $L_x/L_{\rm opt} \approx 30$ but has no strong features that can be associated with the normal star as in Her X-1 and Cyg X-2. Recently, Seitzer *et al.* (1979) announced the discovery of a 5.6 hr photometric period in the optical counterpart of 2A 1822−371, thus greatly strengthening its similarity to 4U 2129+47. Here we present the results of all our spectroscopic, photometric, and photographic observations at CTIO and Kitt Peak together with X-ray spectral and temporal information obtained from the *Ariel 5* satellite.

[1] Visiting Astronomer, Cerro Tololo Inter-American and Kitt Peak National Observatories, which are operated by the Associated Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

II. OPTICAL OBSERVATIONS

a) *Spectroscopy*

We observed our counterpart of 2A 1822−371 with the Cerro Tololo Inter-American Observatory 4 m telescope on 1978 May 4. The SIT vidicon spectrometer (Attwood *et al.* 1979) with a 600 line mm^{-1} grating and 400 μm ($\equiv 2\overset{''}{.}7$) slit gave an average wavelength resolution of 13 Å (based on measurements of calibration spectra) and covered the range 3400–5000 Å. The spectra were reduced with the standard CTIO analysis system. The two-dimensional sensitivity of the SIT and the long slit enable sky background to be subtracted from the area immediately around the star. Two sets of observations were made, one starting at 0514 UT for 73 minutes, the other at 0950 UT for 30 minutes. Figure 1 shows these spectra divided into three approximately equal observations, together with the sum of all the data. Wavelength calibration was performed in the usual way by comparison with standard lamps, but the resultant accuracy is only ~5 Å (similar to Canizares, McClintock, and Grindlay 1979) and is least accurate at the ends of the spectrum. Although the spectra have been calibrated to absolute flux units by comparison with standard stars, the estimated errors are at least ~25% because of poor seeing conditions and very thin cirrus. However, accurate magnitudes and colors were obtained later and are discussed below. Binary phases for the central time of each spectrum are computed from our refined ephemeris given in § II*d*.

b) *Line Identifications*

The most prominent features on these spectra are listed in Table 1 together with their equivalent widths on the total summed spectrum. The presence of the C III/N III complex at $\lambda\lambda$4640–4650 and He II λ4686 has already been

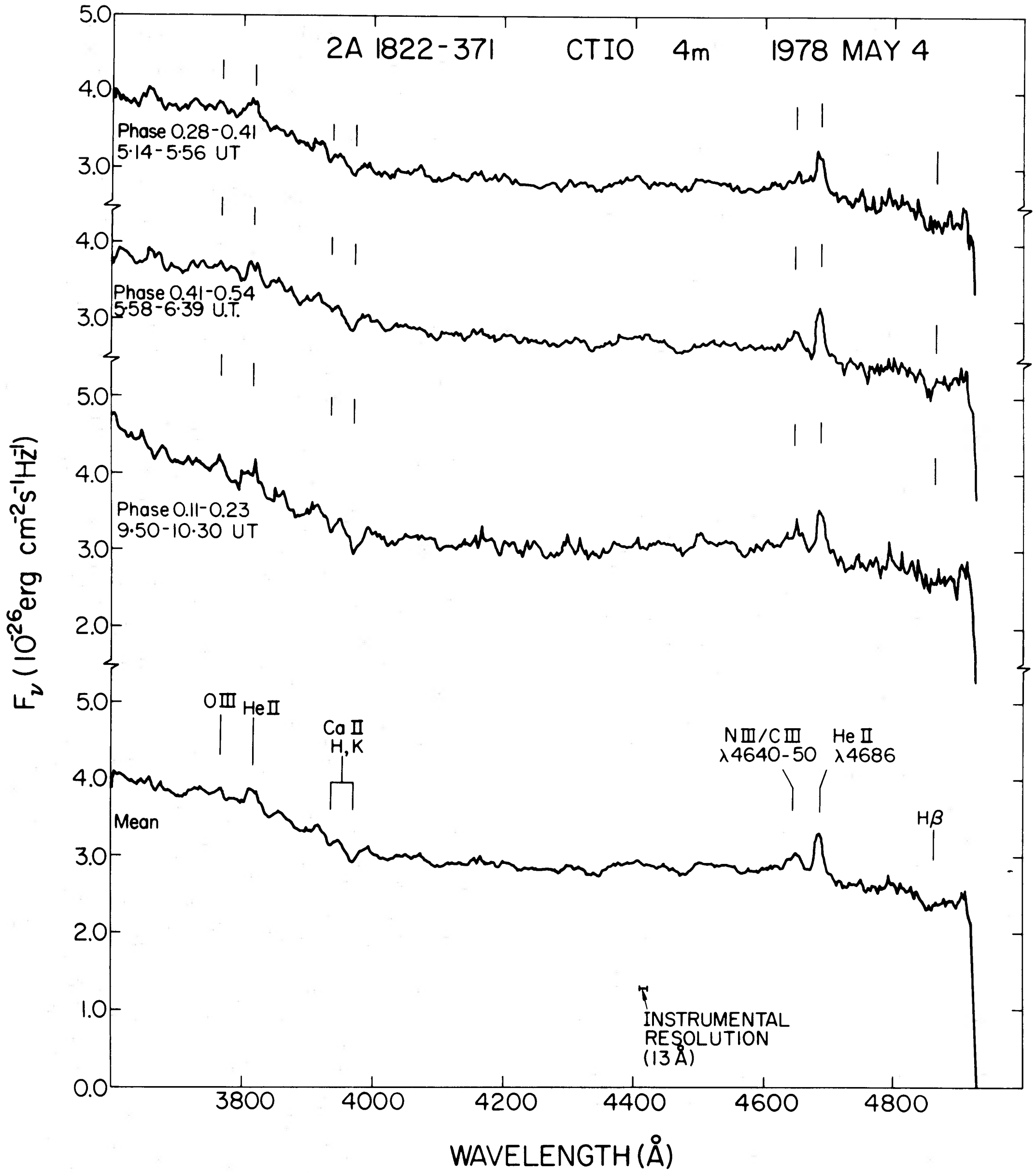

FIG. 1.—Spectra of 2A 1822−371 taken with the CTIO 4 m and SIT vidicon on 1978 May 4 UT with a resolution of ~ 13 Å. Suggested identifications are marked and listed in Table 1. The top 3 spectra are of approximately 30 minutes integration each; their sum is at the bottom. The binary phase is computed from the ephemeris given in the text.

announced by Griffiths *et al.* (1978), and these two features are now the classical indicators of X-ray source optical counterparts. The λλ4640–4650 lines are most probably the result of selective enhancement by the Bowen fluorescence mechanism, a model first suggested by McClintock, Canizares, and Tarter (1975, hereafter MCT). However, it should be noted that in our spectra there is no evidence for the N III lines at λλ4097, 4101, which are produced by the same Bowen process responsible for the λλ4640–4650 emission. The λ4100 blend is often obscured in most optical counterparts by Hδ emission (e.g., Sco X-1), but it is clearly present in the burster counterparts (Canizares, McClintock, and Grindlay 1979) where the Balmer emission is very weak. In 2A 1822−371 there is weak, broad Hβ absorption (possibly slightly blueshifted) but no feature at Hγ, and therefore there should be no Balmer contamination at λ4100. The Ca II H and K and Hβ absorption lines suggest the presence of an ~G–K star (although the Hβ absorption may be too broad to be normal), and we discuss this further below. At this high galactic latitude ($b = -11^\circ.3$) the Ca II is unlikely to be interstellar.

The most unusual features of the spectrum are the two broad emission lines in the ultraviolet, at λλ3765 and

TABLE 1

2A 1822 – 371 LINE FEATURES

Wavelength (Å)	Identification	Equivalent Width[a] (Å)	Velocity Width ($km\ s^{-1}$)
3765	O III	+0.4	too weak
3815	He II	+1.1	986
3930	Ca II H, K	−0.3	too weak
3965		−1.4	740
4640–4650	C III/N III	+1.5	blend
4686	He II	+2.5	500
4850	Hβ	−1.3	776

[a] Positive numbers denote emission features; negative are absorption.

3815, of approximately equal intensity. Canizares, McClintock, and Grindlay detect the O III Bowen lines at λλ3750 and 3800 in the bursters, and it is possible that these are also responsible here. The same multiplet also produces O III λ3811, but this is unlikely to account for the λ3815 feature since this line is an order of magnitude weaker than the λ3760 lines in planetary nebulae (where the Bowen mechanism operates; see MCT). He I λλ3769, 3820 is a similarly unlikely identification, given the absence of the much stronger lines at λλ4026, 4471 (we note, though, that there is a weak, broad absorption feature at λ4471). The broad feature at λ3815 is also evident but weaker in the burster spectra of Canizares *et al.*, and they suggest the O VI doublet at λλ3811, 3834 as a possible candidate. This doublet is present in some planetary nebulae and Wolf-Rayet stars and is seen over a wide range of line widths (Smith and Aller 1969). However, we consider it unlikely in the case of 2A 1822−371 because our feature is not broad enough to include the λ3834 position, and this doublet always has the lines about equal in intensity. Instead we consider the He II λ3814 line (and/or possibly λ3796) to be the most likely candidate given the well-established presence of λ4686, although we note that there is no special reason why this line should be enhanced relative to others in the Pickering series. Hence, a contribution from several of these suggested identifications is still highly probable, especially given the slightly greater width of this feature as compared with λ4686.

c) *Photometry*

As mentioned above, the observing conditions under which we obtained our spectroscopic results were not suitable for deriving accurate magnitudes and colors. We therefore obtained measurements on 1979 July 4.3211 UT with the Kitt Peak National Observatory 2.1 m telescope and computer photometer using a 20″ diaphragm under conditions of reasonable seeing and completely clear skies. These yielded $V = 15.29 \pm 0.02$, $V-R = +0.03 \pm 0.02$, $B-V = +0.08 \pm 0.02$, and $U-B = -0.93 \pm 0.03$. These errors are statistical only; there is a further uncertainty of ~0.05 mag in the extinction correction, and transformation onto the standard *UBVR* system, except in $U-B$ where it is ~0.1 mag. The error is largest in $U-B$ because of the extreme blueness of the object (and hence increased uncertainty in transforming to the standard system) and the large air-mass correction. This is almost a magnitude brighter than the admittedly inaccurate magnitudes measured when the counterpart was discovered in 1978 and supports the view that the object is variable.

d) *Photometric Variability*

We obtained a total of six blue and two red plates of this field from CTIO during 1978 and 1979, using the 1 m telescope and image tube camera. These were nitrogen-baked IIa-O plates with filters to approximately match the standard *B* and *R* passbands. Exposures were typically 10 minutes. We used the Berkeley PDS microdensitometer to scan the X-ray star and 28 other stars on each plate, and reduced these measures to pseudomagnitudes using programs described by Thorstensen, Charles, and Bowyer (1980). To convert the blue measures to approximate true magnitudes we used a plate of a photoelectric sequence near M5 (Arp 1962) and applied the true versus pseudomagnitude relation derived from this plate to the plate of 4U 1822−371 taken under the most closely matching conditions of seeing and air mass. We thus obtained approximate magnitudes of the field stars which allowed us to remove the considerable nonlinearity of the pseudomagnitudes. We estimate that the resulting magnitude scale is linear to ~20%, except for the brightest stars, which are heavily saturated. The external error of the magnitudes themselves is estimated to be approximately 0.5 mag. We then tested for variability in the following manner. First, we averaged the pseudomagnitudes from all the blue plates to reduce scatter and then linearized them using the derived magnitudes of a few stars in the field. We then plotted the linearized magnitudes from each plate against these averages. The scatter about a polynomial fit is a measure of the sensitivity of our data to variations.

The results of these procedures are as follows. We obtain $B = 14.8$ for 2A 1822−371, considerably brighter than our Kitt Peak values but consistent within the large errors possible in our method. The blue plates do show some evidence for low-amplitude variations, considerably smaller than the periodic, short duty-cycle dips observed by Seitzer *et al.* (1979). On two plates, taken 1978 May 1.257 and 1979 May 1.363, heliocentric UT, the star is fainter than the mean by 0.28 and 0.22 mag, respectively. These results correspond to 2.6 and 2.1 σ variations, which are inconclusive individually but collectively suggest irregular variability. The remaining four blue plates show no significant variations with variances around the fit from 0.11 to 0.16 mag. However, the two red plates disagree with each other to a high level of significance (6 σ). From our linearization, we estimate that this corresponds to 0.5 mag of variation.

We consider it likely that the fainter of the two red plates was taken during a minimum. If this interpretation is correct, we are able to refine the ephemeris given by

TABLE 2

Spectrum ($keV\ cm^{-2}\ s^{-1}\ keV^{-1}$)	kT or α	N_x	χ^2 ($\nu = 8$)
Blackbody $I(E) = AE^3[\exp(E/kT) - 1]^{-1} \exp(-\sigma N_x)$	2.4 keV	0	13.4
Brehmsstrahlung $I(E) = A \exp(-E/kT)(kT/E)^{0.4} \exp(-\sigma N_x)$	>8 keV	10^{23}	60
Power law $I(E) = AE^{-\alpha} \exp(-\sigma N_x)$	1.0	4.5×10^{22}	37.0

Seitzer *et al.* (1979). We find that the heliocentric Julian day of minimum light

$$T_{\min} = \text{JD}\ 2{,}444{,}101.959 + \text{E}(0^{\text{d}}.232100 + 1^{\text{d}}.2' \times 10^{-5})\,, \\ -2.4$$

where the period uncertainty is derived by assuming our plate to be taken at phase $0.8 \leq \phi \leq 0.1$. According to this ephemeris, none of our other plates was taken near a photometric minimum.

III. X-RAY OBSERVATIONS

2A 1822−371 was observed by the MSSL proportional counter spectrometer (Experiment C) on board *Ariel 5* from 1978 April 30.6 UT to May 13.2 UT. The experiment was operated in spectral mode for the last 5 days of the observation. After subtracting the X-ray and charged particle backgrounds (as described by Sanford and Ives 1976), various trial spectra were fitted to the data; the best-fitting parameters parameters are given in Table 2. We are thus able to exclude single-component power-law or thermal brehmsstrahlung fits. The data, divided by the best fit, are shown in Figure 2 together with an inset which gives the 90% confidence ($\chi_{\min}^2 + 4.6$) isoprobability contours (see Lampton, Margon, and Bowyer 1976) for the blackbody fit, indicating that the absorbing column $N_x < 10^{23}$ cm^{-2}. In spectral mode the greatest time resolution is one satellite orbit, which is approximately 90 minutes. Under the assumption of a constant hardness ratio F(2–5 keV)/F(5–12 keV), the data give $\chi_\nu^2 = 1.3$ for 20 degrees of freedom, suggesting that the shape of the spectrum did not vary significantly during this period. The first 8 days of observations were made in temporal mode, with a resolution of 64 s, apart from 1 day (May 3.5–4.6) which had a resolution of 0.5 s. The resulting power spectra computed using the technique of Gray and Desikachary (1973) show no evidence for periodicity with a probability $p > 2\%$ for the period range 2 minutes to 6 days, and none for $p > 4\%$ for the range 1.0 to 360 s. In particular, we are able to set a limit $p > 3\%$ for any modulation at the known binary period of 5.57 hr. The data were also examined for bursts; none were detected, the 5 σ limits being $\gamma = L$ (steady)/L (burst) > 0.2 and $\gamma > 0.25$ for the 64 s and 0.5 s data, respectively.

The blackbody nature of the spectrum could well be due to Compton scattering of the X-rays in a hot gas surrounding a central source; e.g., this effect seems to modify the brehmsstrahlung spectrum of Sco X-1 to a smaller extent (Lamb and Sanford 1979). To produce a blackbody spectrum, the scattering optical depth τ_e must be $\gtrsim 10$, which implies $N_e \gtrsim 10^{23}$ cm^{-2}, and suggests that this material is strongly photoionized; so the optical lines could not originate in this region. However, the apparent lack of short-term variability precludes a close comparison with Sco X-1.

IV. DISCUSSION

The known binary period of this system allows us to severely constrain its properties. Application of Kepler's law shows the orbital separation A to be $1.6\,(m_x + m_n)^{1/3}$ $R_\odot$, where m_x and m_n are, respectively, the masses of the compact X-ray emitting object and the normal star in solar units. If $m_x = 1$, then $1.6 < A/R_\odot < 2$ for $0.1 < m_n < 1$. If the normal star fills its Roche lobe so as to provide a source for mass transfer, and $m_n < 1$, then from Paczyński (1971) its radius is less than 0.8 $R_\odot$. If it furthermore follows a lower main-sequence mass-radius

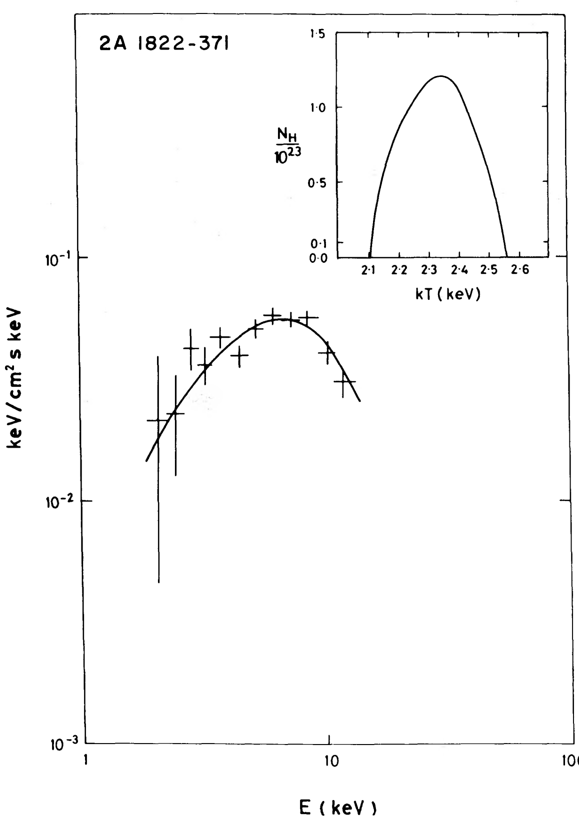

FIG. 2.—X-ray spectrum of 2A 1822−371 obtained with the MSSL proportional counter spectrometer onboard *Ariel 5*. The inset shows the $\chi_{\min}^2 + 4.6$ contour (90% confidence) for the best-fitting blackbody spectrum.

relation, then $0.6 < m_n < 0.8$, from expressions given by Robinson (1976). This corresponds to a spectral type of early to mid K (Allen 1973), if the star is on the main sequence. It seems likely, then, that the Ca II absorption originates in the atmosphere of the normal star, perhaps in an X-ray illuminated portion. Such behavior is seen in 4U 2129 + 47 (Thorstensen *et al.* 1979). The Hβ also might arise from the normal star, but its large width suggests that it arises in a rapidly rotating accretion disk.

Since our spectra go to rather short wavelengths, and since this is a relatively bright, virtually unreddened X-ray star, our spectra show the ultraviolet emission lines with unusual clarity. Similar features are detected in the transient X-ray burster Cen X-4 (Canizares, McClintock, and Grindlay 1980). The optical similarities, in the face of the quite different X-ray behaviors of these two objects, suggest that the optical emission is not intimately linked to the X-ray behavior. The optical emission lines probably originate in the outer parts of an accretion disk, or perhaps in the normal star's X-ray heated atmosphere. The persistence of the lines at varying binary phase (Fig. 1) argues against this second interpretation, however. The UV lines in these systems may thus all have a common origin but firm identifications and interpretation must await higher-quality spectra. A more detailed analysis of the binary parameters will require radial velocity measurements of the absorption and emission lines through the orbital period, preferably with simultaneous optical and X-ray photometry so as to estimate the relative contributions of the primary and reprocessed radiation.

We thank Drs. K. Mason and I. Tuohy for information that enabled us to resolve an ambiguity in the improved binary period and the referee for a useful comment on our suggested He II identification. P. B. acknowledges the financial support of the UK Science Research Council. The optical work of P. C. and J. T. was supported by NSF grant AST78-06873.

REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (3d ed.; London: Athlone Press).
Arp, H. C. 1962, *Ap. J.*, **135**, 311.
Attwood, B., Ingerson, T., Lasker, B., and Osmer, P. 1979, *Pub. A.S.P.*, **91**, 120.
Bradt, H. V., Doxsey, R. E., and Jernigan, J. G. 1979, *Adv. Space Expl.*, **3**, in press.
Canizares, C. R., McClintock, J. E., and Grindlay, J. E. 1979, *Ap. J.*, **234**, 556.
———. 1980, *Ap. J.* (*Letters*), **236**, L55.
Cowley, A. P. 1979, Review presented at NATO Advanced Study Institute on Galactic X-Ray Sources, Cape Sounion, Greece, May 28 to June 8.
Cowley, A. P., Crampton, D., and Hutchings, J. B. 1979, *Ap. J.*, **231**, 539.
Gray, D. F., and Desikachary, K. 1973, *Ap. J.*, **181**, 523.
Griffiths, R. E., Gursky, H., Schwartz, D. A., Schwarz, J., Bradt, H., Doxsey, R. E., Charles, P. A., and Thorstensen, J. R. 1978, *Nature*, **276**, 247.
Lamb, P., and Sanford, P. W. 1979, *M.N.R.A.S.*, **188**, 555.
Lampton, M., Margon, B., and Bowyer, S. 1976, *Ap. J.*, **208**, 177.
Li, F. K., van Paradijs, J. A., Clark, G. W., Jernigan, J. G., Laustsen, S., and Zuiderwijk, E. J. 1978, *Nature*, **276**, 799.
McClintock, J. E., Canizares, C. R., and Tarter, B. C. 1975, *Ap. J.*, **198**, 641 (MCT).
Paczyński, B. 1971, *Ann. Rev. Astr. Ap.*, **9**, 183.
Robinson, E. L. 1976, *Ap. J.*, **203**, 485.
Sanford, P. W., and Ives, J. C. 1976, *Proc. Roy. Soc. London, A*, **350**, 491.
Seitzer, P., Tuohy, I. R., Mason, K. O., Middleditch, J., Nelson, J., and White, N. E. 1979, *IAU Circ. 3406*.
Smith, L. F., and Aller, L. H. 1969, *Ap. J.* **157**, 1245.
Thorstensen, J., Charles, P., and Bowyer, S. 1980, *Ap. J.*, **238**, 964.
Thorstensen, J., Charles, P., Bowyer, S., Briel, U. G., Doxsey, R. E., Griffiths, R. E., and Schwartz, D. A. 1979, *Ap. J.* (*Letters*), **233**, L57.

P. BARR: Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, England

P. CHARLES and J. THORSTENSEN: Space Sciences Laboratory, University of California, Berkeley, CA 94720