THE ASTROPHYSICAL JOURNAL, 258:240–244, 1982 July 1

ULTRAVIOLET SPECTRA OF THE X-RAY TRANSIENT A0538 – 66

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Received 1981 September 3; accepted 1982 January 15

ABSTRACT

Ultraviolet spectra were obtained before and after the optical spectrum changed from absorption to emission lines. The continuum brightness dropped by a factor of 2. Spectra with bright continua show N v, Si iv, and C iv in absorption, while the spectrum with fainter continuum has these lines in emission. The emission lines of N v and Si iv are anomalously bright compared with C iv. The brighter spectra indicate an effective temperature of 25,000 K, while the fainter continuum indicates a somewhat lower temperature. Probable interstellar absorption lines due to galactic halo and the LMC interstellar medium are observed.

Subject headings: galaxies : Magellanic Clouds – stars: emission-line — stars: individual — ultraviolet: spectra — X-rays: sources

I. INTRODUCTION

White and Carpenter (1978) discovered X-ray outbursts from A0538 – 66, and subsequent observations have shown that outbursts recur approximately (but not exactly) every 16.7 days (Skinner *et al.* 1980). The optical counterpart of the outbursts source was identified by Johnston *et al.* (1980) as a 15th magnitude B star which varies by about one magnitude. A normal B star of this magnitude would be a member of the LMC. Assuming the distance of the LMC, outburst luminosities reach 10^{39} ergs s^{-1}. The X-ray bursts are relatively soft, with $kT \approx 7$ keV, and decay times range from hours to days. Skinner (1980) has found optical flares of about two magnitudes associated with the X-ray outbursts. Charles and Thorstensen (1981) have recently observed a two-magnitude brightening, with increasing emission line strength during the decay. Hutchings, Cowley, and Crampton (1981) found line profiles indicative of a shell star a few weeks later. Pakull and Parmar (1981) reported that the star grew fainter between April and September 1980 and that it changed from an absorption-line to an emission-line spectrum. If is thus a Be star, one of a dozen such stars identified with X-ray sources (Rappaport and van den Heuvel 1981).

We have obtained ultraviolet spectra with the *IUE* satellite about 3 months apart, on June 25 (SWP 9365, LWR 8199), July 2 (SWP 9420), and September 25 (SWP 10221, LWR 8899) 1980. The earlier spectra show an early B star continuum with Si iv and C iv absorption lines, while the later ones show a cooler, fainter continuum with Si iv and N v in emission. We discuss the origin of the emission lines.

[1] Guest Observer with the *International Ultraviolet Explorer* satellite, which is sponsored and operated by the U.S. National Aeronautics and Space Administration, by the Science Research Council of the U.K., and by the European Space Agency.

II. OBSERVATIONS

Five low-dispersion spectra of the candidate star Q identified by Johnston, Griffiths, and Ward (1980) were obtained with the *IUE* satellite. The instrumentation is described by Boggess *et al.* (1978). The star was located by performing a blind offset from an SAO Catalogue star to the position given by Johnston, Griffiths, and Ward and verifying the identification of the field with a small Fine Error Sensor image. The exposures (all obtained with the large aperture) are listed in Table 1 along with the phases in the $16^{d}.7$ outburst period according to the ephemeris of Johnston, Griffiths, and Ward. Phases according to the ephemeris of Skinner *et al.* (1980) would be later by about 0.05. Due to the proximity of star R, the Fine Error Sensor gave only upper limits to the object's brightness of $m_V > 14.5$. We do not have simultaneous X-ray coverage, but during all of these observations the star was much fainter than $m_B \approx 13.2$ reported by Skinner (1980) for the outbursts.

The three short wavelength spectra are shown in Figure 1. The background of spectrum SWP 10221 may be slightly contaminated by light from stars R and D which were located at the ends of the large aperture, but various extractions from the line-by-line spectrum show that the uncertainty introduced is smaller than 10%. In Figure 2 the average of SWP 9365 and SWP

TABLE 1
IUE IMAGES

Exposure	JD	Φ	Exposure (min)
SWP 9365	2,444,416.3395	0.56	60
SWP 9420	2,444,423.2268	0.97	60
SWP 10221	2,444,508.5500	0.10	60
LWR 8119	2,444,416.2933	0.56	60
LWR 8892	2,444,508.5866	0.10	40

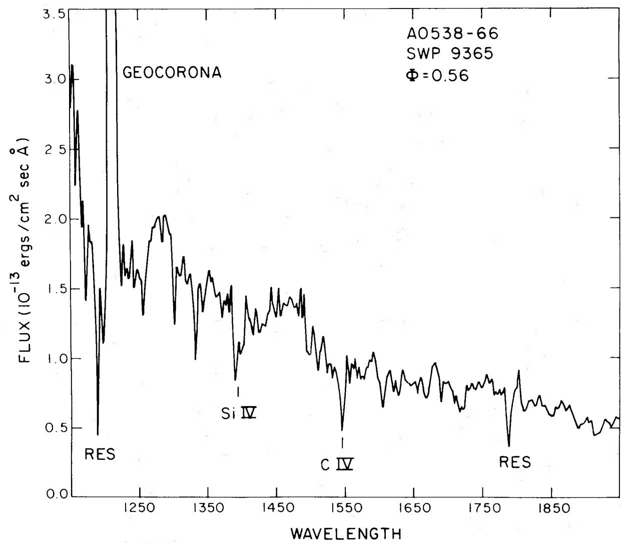

FIG. 1*a*

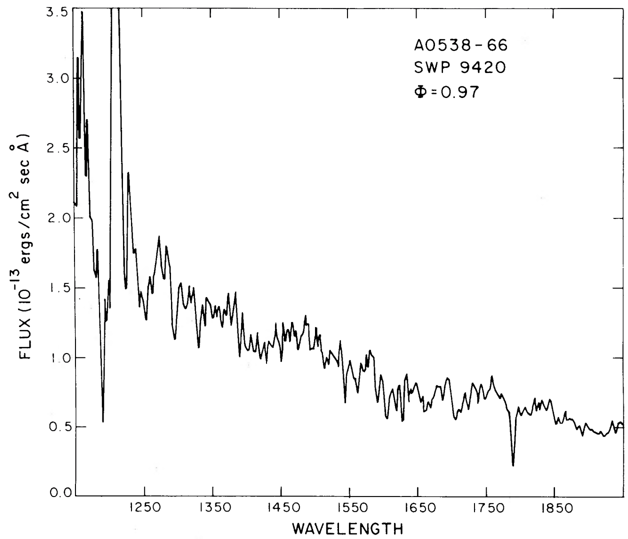

FIG. 1*b*

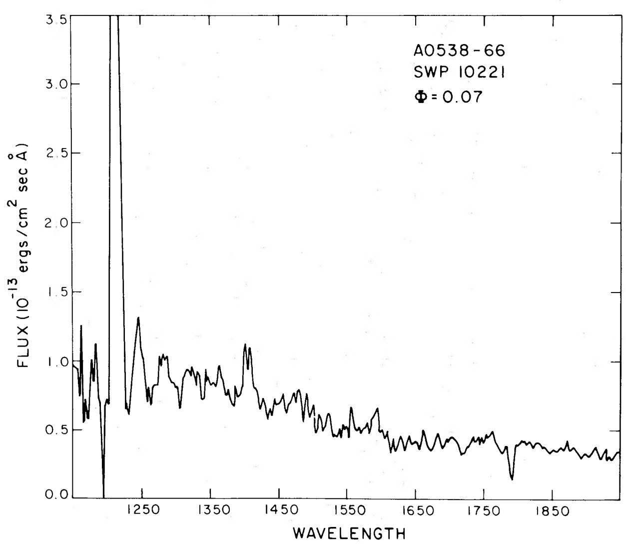

FIG. 1*c*

FIG. 1.—Short wavelength spectra of A0538 – 66. The low points at 1193 Å and 1790 Å are reseau marks.

9420 is compared with the 25,000 K, log $g = 4.0$ solar abundance model of Kurucz (1979). The model fluxes have been reddened with $E(B-V) = 0.06$ (e.g., Koorneef and Mathis 1981) and the galactic extinction law of Seaton (1980). The agreement between the models and the observed spectrum would not be improved significantly by including LMC extinction as well. Because of the wide range of strengths of the 2200 Å feature in the LMC (Nandy *et al.* 1980), it is difficult to place a firm upper limit on the amount of LMC extinction present, but a color excess greater than 0.15 mag should have been easily noticeable. The long wavelength spectrum LWR 8119 agrees with this picture. The continuum from the later spectra, SWP 10221 and LWR 8899, indicates a somewhat lower temperature, roughly 20,000 K.

The effective temperature of 25,000 K determined from the earlier spectra is at the low end of the range given by the spectral classification of O9–B1 V–III assigned by Pakull and Parmar (1981) based on the Hγ equivalent width in February 1980 according to the effective temperature scale of Böhm-Vitense (1981). The photometry of Pakull and Parmar from 1980 February through 1980 April suggests a somewhat lower temperature. Comparison of the continuum flux at 1900 Å and the average V magnitude from 1981 February through 1981 April with Kurucz (1979) model atmospheres yields a still lower estimate of 21,000 K. The discrepancy is about what might be expected from the variability during this time as shown by Pakull and Parmar. The 20,000 K effective temperature obtained from the September spectra is reasonably consistent with the photometry of Pakull and Parmar. By 1981 January, the star had faded by 0.2 mag and cooled to 14,500 K (Murdin, Branduardi-Raymont, and Parmar 1981).

Several features appear in the spectra of Figure 1 which can be identified as probable interstellar lines. The absorptions at λ1260 (Si II), λ1300 (O I, Si II, or stellar Si III), λ1335 (C II), λ2800 (Mg II) all have equivalent widths of about 1 Å. They appear in low-dispersion spectra of LMC X-4 which we obtained with the same instrument. The high-dispersion spectra of Savage and deBoer (1979) demonstrate that the equivalent widths are the result of the spread in velocity of interstellar material in the galactic halo and the LMC. The interstellar lines therefore provide some confirmation that the observed star is an LMC member rather than a foreground object. It must be noted, however, that somewhat similar features appear in low-resolution spectra of the nearby dwarf novae U Gem (Fabbiano *et al.* 1981) and SS Cyg in outburst (Heap *et al.* 1978).

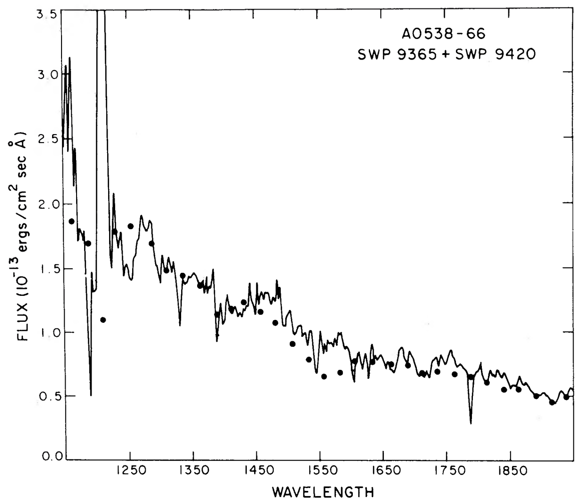

FIG. 2.—Average of SWP 9365 and SWP 9420 compared with a 25,000 K, log $g = 4.0$ Kurucz model.

Interstellar absorption lines of Si IV and C IV are also reported by Savage and deBoer, but the 4 Å equivalent width absorption features in SWP 9365 are much too strong to be interstellar. The equivalent widths of these absorptions are only about half as large in SWP 9420 (with interstellar absorption accounting for roughly half of that). In SWP 10021 N V, Si IV, and C IV are in emission, though the C IV is quite weak. The Si IV flux is 5.1×10^{-13} ergs cm^{-2} s^{-1}. The interpretation of the N V feature in SWP 9420 is unclear, due to the difficulty of setting the continuum level, but it is definitely in absorption in SWP 9365 and in emission in SWP 10221. The emission feature at 1590 Å in SWP 10021 is not obviously due to noise, but we can suggest no identification.

Since the spectral shapes of SWP 9365 and 9420 indicate an early B star, it is possible that the C IV and Si IV absorptions arise in a wind. P Cygni emission profiles are not apparent, but this is also true for low resolution spectra of Cyg X-1, which does have a strong wind (Dupree *et al.* 1978). Wavelength shifts of several angstroms can occur in *IUE* low dispersion, large aperture spectra, but the interstellar lines provide wavelength standards at $v_{LSR} \approx 120$ km s^{-1}. The *IUE* resolution is about 6 Å, but the centers of well-defined absorption or emission features can be located to about ± 1 relative to other features in the same spectrum. It appears that the absorption features in the two earlier spectra are at rest with respect to the LMC, while the emission in the last spectrum seems to be redshifted by around 600 km s^{-1}. This should be regarded as a marginal result, however. It is an intriguing speculation that the emission lines are the emission parts of P Cygni profiles, while the parts of the wind that would normally produce the P Cygni absorption are ionized by X-rays. Effects of this sort have been observed in Vela X-1 (Dupree *et al.* 1980). It is not immediately apparent how to account for the weakness of C IV compared with Si IV and N V in this scheme.

III. DISCUSSION

The ultraviolet continua indicate that the luminosity of A0538−66 dropped by about 10^{37} ergs s^{-1} between 1980 July and 1981 September, and the optical data of Murdin, Branduardi-Raymont, and Parmar (1981) suggest a further decrease by a similar amount by 1981 January. There is not yet a systematic study of the ultraviolet variability of Be stars, but from the typical variability in *V* magnitude and color (e.g., Feinstein 1975) of Be stars, it is likely that the continuum changes described here are intrinsic to the Be star, independent of the X-ray source. As the variations of Be stars are not understood, this is not very enlightening. The continuum changes are consistent with changing temperature and constant stellar radius, within the factor of 2 uncertainty associated with the uncertainty in the temperature determination.

The most striking feature of the observations is the appearance of strong emission lines as the continuum fades. This is a common occurrence in dwarf novae, a class of weaker X-ray sources, which show C IV and Si IV absorption at maximum and emission at minimum (e.g. Heap *et al.* 1978; Szkody 1981). Be stars have been extensively observed in the ultraviolet, but the C IV, Si IV, and N V lines generally show either P Cygni profiles or pure absorption. The presence of N V in the cooler stars shows that some input to the energy or ionization of Be star winds beyond that of the photospheric radiation field is needed (e.g., Cassinelli, Castor, and Lamers 1978). Panek and Savage (1976) reported the equivalent widths of the Si IV and C IV absorption lines changed from about 3 Å to about 7 Å in γ Cas. Slettebak and Snow (1976) observed a transient emission feature in the Si IV, Mg II, and Hα lines of γ Cas, but it was extremely weak compared with the emission seen in SWP 10221.

There are several possibilities for the formation of the emission lines. The gas could be optically thick or thin, and it could be collisionally ionized or photoionized. The remarkable strength of the Si IV and N V lines relative to C IV provides some information on the line forming region. The silicon and nitrogen lines are about 5 times as strong as the C IV doublet. Several other X-ray sources show stronger N V than C IV. Sco X-1 (Willis *et al.* 1980), HZ Her (Dupree *et al.* 1978; Gursky *et al.* 1980), Cen X-4 during its 1979 outburst (W. Blair, private communication), GK Per during its 1980 outburst (C. C. Wu 1981, private communication), and Cyg X-2 (Maraschi, Tanzi, and Treves 1980) all have N V stronger than C IV λ1550, but the Si IV lines are substantially weaker than C IV. Only the novalike variable AE Aqr (Jameson, King, and Sherrington 1980; Hartmann and Raymond 1980) has both N V and Si IV much stronger than the C IV lines. The "normal" situation for dwarf novae at minimum, AM Her stars, and old novae seems to be C IV emission several times stronger than Si IV and N V (Heap *et al.* 1978; Raymond *et al.* 1979; Hartmann and Raymond 1980; Szkody 1981; Krautter *et al.* 1981). The approximate equality of the absorption equivalent widths in SWP 9365 and the inferred photospheric temperature of 25,000 K indicate a normal carbon-to-silicon abundance ratio (cf. Henize, Wray, and Parsons 1981), so the abnormal line strengths must be explained in terms of the physical conditions in the emitting region.

The transition zone of a late-type star is an example of a collisionally ionized plasma with a smooth temperature distribution through the range 5×10^4–3×10^5 K. Optical depths in the strong lines are generally in the range 0.1–10, but the lines seem to be effectively thin, so that photons escape after a few scatterings. Many such stars have been observed with *IUE* (e.g., Hartmann, Dupree, and Raymond 1982; Ayres, Marstad, and Linsky 1981), and all show C IV λ1550 several times stronger than Si IV and N V if these lines are present. This is basically a reflection of the abundances of the three elements and fact that the temperatures of formation of the silicon and nitrogen lines closely bracket that of the carbon doublet. The N V line can be enhanced relative to C IV if the emission is dominated by 10^6 K gas (e.g., Raymond and Foukal 1982), but that would imply a fairly strong He II λ1640 recombination line (Hartmann *et al.* 1979), and it would produce very weak Si IV. Thus, we conclude that effectively optically thin, collisionally ionized gas does not produce the observed emission lines. In the optically thick limit for collisionally ionized gas, consideration of the relevant ionization potentials and oscillator strengths leads to the expectation that N V would be somewhat brighter than C IV, but Si IV would again be weaker.

Similar difficulties arise with interpretation of the emission-line spectrum in terms of photionized gas. Models of X-ray ionized gas which is effectively thin in the emission lines (Hatchett, Buff, and McCray 1976) yield C IV emission several times stronger than N V and Si IV. More recent calculations by London, McCray, and Auer (1981) indicate that the line emission from an X-ray heated atmosphere is likely to be optically thick, but the best studied case, HZ Her, is observed to have weaker Si IV than C IV emission. Gas illuminated by very soft X-rays is observed in the AM Her stars, and the C IV: Si IV: N V ratios are about 4:1:1 (Raymond *et al.* 1979). Thus, neither observations nor theory leads to a convenient explanation for the line ratios.

We are left with various ad hoc and generally unappealing hypotheses. The nitrogen and silicon emission might be more or less unrelated. For instance, the 20,000 K photosphere could maintain an envelope or disk several stellar radii in extent in which silicon in largely Si IV and carbon is mostly C III. A separate emission region, perhaps close to the X-ray source, would be needed to account for the N V. Alternatively, it might be possible to construct a wind in which the emission and absorption parts of the P Cygni profile of the C IV doublet nearly cancel, while the emission parts of the silicon and nitrogen lines dominate. A standard spherically symmetric wind would not be likely to produce such line ratios, and no models for disk geometries are available.

At present, we cannot tell whether the emission lines are basically due to X-ray heating or to energy dissipation related to the shell ejection. The upper limit to the nonoutburst X-ray luminosity given by Pakull and Parmar (1981) is about 50 times larger than the combined luminosity of the UV lines, but X-ray heating could perhaps be ruled out by more sensitive limits.

The author thanks the staff of the *International Ultraviolet Explorer* for help in aquisition and reduction of the observations and J. Patterson, D. Lamb, and L. Hartmann for helpful discussions. This work was supported by NASA grant NAG 5-87.

REFERENCES

Ayres, T. R., Marstad, N. C., and Linsky, J. L. 1981, *Ap. J.*, **247**, 545.
Boggess, A. P., III, *et al.* 1978, *Nature*, **275**, 372.
Böhm-Vitense, E. 1981, *Ann. Rev. Astr. Ap.*, **19**, 295.
Cassinelli, J. P., Castor, J. I., and Lamers, H. G. J. I. M. 1978, *Pub. A.S.P.*, **90**, 496.
Charles, P. A., and Thorstensen, J. R. 1981, *IAU Circ.* 3570.
Dupree, A. K. *et al.*, 1978, *Nature*, **275**, 400.
Dupree, A. K. *et al.*, 1980, *Ap. J.*, **238**, 968.
Fabbiano, G., Hartmann, L., Raymond, J., Steiner, J., and Matilsky, T. 1981, *Ap. J.*, **243**, 911.
Feinstein, A. 1975, *Pub. A.S.P.*, **87**, 603.
Gursky, H., *et al.* 1980, *Ap. J.*, **237**, 163.
Hatchett, S., Buff, J., and McCray, R. 1976, *Ap. J.*, **206**, 847.
Hartmann, L., and Raymond, J. C. 1980, in *The Universe at Ultraviolet Wavelengths*, ed. R. D. Chapman (Washington: NASA), p. 495.
Hartmann, L., Davis, R. J., Dupree, A. K., Raymond, J. C., Schmidtke, P. C., and Wing, R. F. 1979, *Ap. J.* (*Letters*), **233**, L69.
Hartmann, L., Dupree, A. K., and Raymond, J. C. 1982, *Ap. J.*, **252**, 214.
Heap, S. R., *et al.* 1978, *Nature*, **275**, 385.
Henize, K. G., Wray, J. D., and Parsons, S. B. 1981, *Pub. A.S.P.*, **86**, 1659.
Hutchings, J. B., Cowley, A. P., and Crampton, D. 1981, *IAU Circ.* 3585.
Jameson, R. F., King, A. R., and Sherrington, M. R. 1980, *M.N.R.A.S.*, **191**, 559.
Johnston, M. D., Griffiths, R. E., and Ward, M. J. 1980, *Nature*, **285**, 26.
Koorneef, J., and Mathis, J. S. 1981, *Ap. J.*, **245**, 49.
Krautter, J., Klare, G., Wolf, B., Wargau, W., Drechsel, H., Rahe, J., and Voght, N., *Astr. Ap.*, **98**, 27.
Kurucz, R. 1979, *Ap. J. Suppl.*, **40**, 1.
London, R. A., McCray, R., and Auer, L. H. 1981, *Ap. J.*, **243**, 970.
Maraschi, L., Tanzi, G., and Treves, A. 1980, *Ap. J.* (*Letters*), **241**, L23.
Murdin, P., Branduardi-Raymont, G., and Parmar, A. N. 1981, *M.N.R.A.S.*, **196**, 95P.
Nandy, K., Morgan, D. H., Willis, A. J., Wilson, R., Gondhalekhar, P. M., and Houziax, L. 1980, *Nature*, **283**, 725.
Pakull, M., and Parmar, A. 1981, *Astr. Ap.*, **102**, L1.
Panek, R. J., and Savage, B. D. 1976, *Ap. J.*, **206**, 167.
Rappaport, S., and van den Heuvel, E. P. J. 1981, in *IUA Symposium 98*, *Be Stars*, ed. M. Jaschek and H. G. Groth (Dordrecht: Reidel), in press.
Raymond, J. C., and Foukal, P. 1982, *Ap. J.*, **253**, 323.
Raymond, J. C., Black, J. H., Davis, R. J., Dupree, A. K., Gursky, H., Hartmann, L., and Matilsky, T. 1979, *Ap. J.* (*Letters*), **230**, L95.
Savage, B. D., and deBoer, K. S. 1979, *Ap. J.* (*Letters*), **230**, L27.
Seaton, M. J. 1979, *M.N.R.A.S.*, **187**, 37P.

Skinner, G. K. 1980, *Nature*, **288**, 141.
Skinner, G. K., *et al.* 1980, *Ap. J.*, **240**, 619.
Slettebak, A., and Snow, T. P., Jr. 1978, *Ap. J.* (*Letters*), **224**, L127.
Szkody, P. 1981, *Ap. J.*, **247**, 577.
White, N. E., and Carpenter, G. F. 1978, *M.N.R.A.S.*, **183**, 11P.
Willis, A. J., *et al.* 1980, *Ap. J.*, **237**, 596.

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