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IUE OBSERVATIONS OF A LUMINOUS M SUPERGIANT THAT EXHIBITS EMISSION CONTINUUM IN THE FAR ULTRAVIOLET

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ABSTRACT

IUE observations of the late-type M supergiant TV Gem (M1 Iab) have been obtained that reveal strong UV continuum between 1200 and 3200 Å. The continuum is essentially featureless with the exception of a number of broad absorption features in the short wavelength spectral range. UV emission from this star is unexpected because earlier ground-based observations give no indication of a possible association with an early companion or circumstellar ionized nebulosity. We find that a B9 or A1 III–IV type star approximately 2–3 magnitudes fainter than the M star could explain the level of UV continuum observed, but a fully self-consistent explanation that includes the $B-V$ color index of TV Gem is not as yet possible. The continuum flux dependence with wavelength in the UV spectral range could be attributed to a high-energy source such as an accretion disc. We suggest TV Gem as a good candidate for *HEAO 2* (*Einstein*) satellite observations because a high-energy object in close proximity to the M star would likely be a source of soft X-ray emission.

Subject headings: stars: binaries — stars: late-type — stars: supergiants — ultraviolet: spectra

I. INTRODUCTION

Observations obtained with the *International Ultraviolet Explorer* (*IUE*) of the luminous M supergiant TV Gem (M1 Iab) reveal an intense continuum in the far ultraviolet. TV Gem is supposedly a cool star (Keenan 1942) not known previously from optical spectra to be associated with an early companion or ionized nebulosity. The UV continuum observed in low dispersion using the short and long wavelength cameras of the *IUE* spectrometer covers the spectral range 1200 Å–3200 Å and does not exhibit high excitation emission lines that generally characterize chromospheres, or forbidden emission lines that typify nebulosity in symbiotic stars (see Gaposchkin 1964). High excitation interacting binaries of which RW Hya (gM2+pec) is considered an example (Kafatos, Michalitsianos, and Hobbs 1980), exhibit forbidden and allowed emission in the visible range that is superimposed on the strong absorption spectrum of the cool M giant primary star. Based upon earlier spectral classification work of Keenan (1942) and Morgan and Keenan (1973) TV Gem does not appear to exhibit such properties.

Equally interesting, however, is the infrared emission observed in TV Gem which has been studied by Gehrz and Woolf (1971) in the infrared bands at 3.5 μm, 4.9 μm, 8.4 μm and 11 μm. They find based on the infrared emission from this star a mass loss rate of $\dot{M} \approx 1.2 \times 10^{-6} M_\odot$ year^{-1} that results in a cool circumstellar silicate shell around the supergiant. TV Gem is identified in the *Two-Micron Catalog* as +20134 (Neugebauer and Leighton 1969). Moreover, microwave observations by Brown *et al.* (1980) suggest TV Gem is also an OH maser star for which the 1665 MHz main emission line has been detected in the direction of this supergiant. Accordingly, this object exhibits a multitude of emission properties that distinguish this M supergiant as a possible microwave, infrared as well as a strong source of UV emission. TV Gem has also been found by Jennings and Dyck (1970) to exhibit polarization in the optical.

If the continuum arises from an unseen companion the absence of strong emission lines suggests the object could be associated with high temperatures and high surface gravities. However, uncertainties in the precise value of interstellar extinction applied to the continuum over the spectral sensitivity range of *IUE* are such that these observations could be explained by a late B or early A giant (III–IV), although a fully

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1980ApJ...241..774M

self-consistent model based on this interpretation cannot as yet be advanced. At this stage, therefore, the nature of the companion to TV Gem is not understood. It is the purpose of this paper to only draw attention to the UV spectral properties of this M supergiant. We describe our observations and analysis in the following sections.

II. ULTRAVIOLET OBSERVATIONS OF TV GEM

IUE observations were obtained 1979 November 25 in low dispersion (~6 Å spectral resolution) of TV Gem using both short (1200 Å–2000 Å) and long (2000 Å–3200 Å) wavelength cameras of the *IUE* spectrometer (Boggess *et al.* 1978). An initial exposure of 120 minutes totally saturated the long wavelength camera using the large entrance aperture (10″×20″). Reasonable signal-to-noise images were obtained on subsequent exposures of 10 minutes in both cameras.

Observations on 1980 January 16 obtained in low and high dispersion showed essentially the same continuum flux level observed previously. Adequate observing time was not available for obtaining good signal-to-noise high dispersion spectra. However, using 2 hour exposures in both short and long wavelength spectral ranges, we were unable to find any trace of line emission or line absorption where the continuum was clearly above the noise level on the photowrite images of the echelle spectrum.

TV Gem (DM+21°1146) is an SRc variable type and has an observed variation in intrinsic luminosity of 182 days (Kukarkin *et al.* 1969). At α (1950)= $06^h08^m50^s.5$, $\delta=+21°52'52''$ this M supergiant lies close to the galactic plane, where $l_{II}=189°04'$, $b_{II}=+01°36'$. From Kukarkin *et al.* (1969) the range in photographic magnitudes for TV Gem appears to be overestimated. Humphreys (1970), Eggen (1967), and Crawford *et al.* (1955) give V magnitudes greater by a value of approximately 1. We consider in § III the extinction and distance derived for TV Gem from optical observations with estimates for UV absorption obtained from our observations.

III. DATA ANALYSIS

TV Gem is known to be a member of the I Geminorum Association that has an estimated distance of 1400 pc (Crawford *et al.* 1955). Humphreys (1970) gives as an apparent magnitude of TV Gem $m_V=6.56$ that is corrected for absorption. Crawford *et al.* (1955) give the absolute magnitude of TV Gem $M_V=-5.7$ and $E(B-V)=+0.44$, that is in agreement with Eggen (1967) who finds a value for absorption $E(B-V)=+0.40$ for the general vicinity of stars in the association of which TV Gem is a member. At 1400 pc we estimate for an $E(B-V)=+0.40$ for a column density in our line of sight $N_{\rm H\,I}\approx1.9\times10^{21}$ cm^{-2}, that corresponds to an average density of the interstellar medium in the direction of TV Gem of $\bar{n}_{\rm H\,I}\approx0.44$ cm^{-3}.

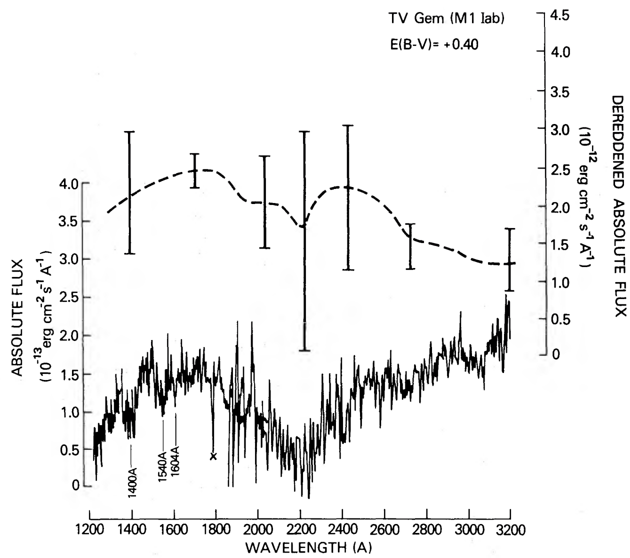

FIG. 1.—TV Gem absolute flux plotted against wavelength from observations obtained 1979 November 25 where both short and long wavelength spectral images are shown together (~6 A spectral resolution). Data were obtained with the 10″×20″ entrance slit of *IUE*. A number of broad absorption features are noticeable in the 1400 Å–1600 Å range. The data corrected for interstellar absorption (*dashed curve*) is shown for an $E(B-V)=+0.40$. Error bars indicate uncertainty in the measured continuum flux level obtained using 10 minute exposures; × indicates a reseau mark.

We derive an estimate for UV extinction for the companion to the M1 supergiant in order to determine if it has correspondingly similar reddening. From the depression of the ultraviolet continuum at wavelengths of ~2200 Å we can estimate an $E(B-V)$ for the companion. Using now the estimated UV absolute continuum flux from our data we note that at 3000 Å the flux is $\sim1.6\times10^{-13}$ ergs cm^{-2} s^{-1} Å^{-1}, and at 2200 Å is $\sim0.25\times10^{-13}$ ergs cm^{-2} s^{-1} Å^{-1}. Spitzer (1978) gives as values for interstellar absorption in the UV at these two wavelengths the quantities 5.5 $E(B-V)$ and 10 $E(B-V)$ at 3000 Å and 2200 Å, respectively. The value obtained here for the 2200 Å extinction feature (Fig. 1) is $E(B-V)=+0.40$, that is comparable to the values obtained for the M supergiant by Eggen (1967) and Crawford *et al.* (1955). Accordingly, these comparable values for absorption for the M supergiant and the UV companion suggests that the UV emission arises from an object that is comparable in distance to that estimated for TV Gem in the optical.

a) *UV Continuum*

In Figure 1 we show the UV spectrum of TV Gem over the entire spectral sensitivity range of the *IUE*. The data have been absolutely calibrated using data reduction software routines developed for the PDP 11/40 computer at NASA Goddard Space Flight Center by D. A. Klingelsmith and R. P. Fahey. The UV

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1980ApJ...241..774M

spectrum has been processed using the corrected intensity transfer function recently implemented in *IUE* data reduction programs. The absolute continuum flux in Figure 1 is unsmoothed and was obtained using 10 minute exposures in both short and long wavelength cameras. Shown also in Figure 1 is the continuum in which an $E(B-V)=+0.40$ absorption correction has been applied to the data using a mean value for the continuum level observed. The error bars indicate the maximum excursion that the dereddened continuum curve undergoes if we consider uncertainties in the measured absolute flux levels. Clearly, the exact value of the continuum as measured at a given wavelength strongly influences the continuum corrected for absorption. As such, the exact dependence of F_λ dereddened with wavelength is difficult to establish. Averaging together spectra obtained on both observing dates that were acquired in identical configurations of the spectrometer, i.e., using the same entrance aperture ($10'' \times 20''$) and exposure times (10 minutes in short and long wavelength cameras) reduces the noise level somewhat, because the effective exposure is 20 minutes. However, these uncertainties are not resolved even when data are added together in this manner.

We find that the smoothed dereddened curve shown in Figure 1 could in fact represent the actual continuum of the UV source. On the other hand, given the range in uncertainties, the continuum dependence F_λ with wavelength could be represented by a straight line that rises slightly toward shorter wavelengths. As yet we cannot determine the nature of the object from this aspect of the data alone. Upon comparing the width of the UV spectrum of TV Gem with other *IUE* spectra obtained of early main-sequence stars that are known not to be in double systems, we find our spectra are consistent with the presence of only a single star in close proximity to the M supergiant.

b) *Broad Absorption Features*

The short wavelength region contains a number of broad absorption features centered approximately at ~1400 Å, 1540 Å and 1604 Å. The low resolution of ~6 Å makes precise identification of these absorption features difficult. The feature centered around 1400 Å is possibly explained by the presence of Si IV lines that appear blended in low dispersion spectra. The Si IV 1400 Å absorption would typify middle B type main-sequence stars (Nandy 1976) as we have found examining low resolution spectra from *OAO 2* of early standard stars. The features identified in Figure 1 persist if the spectra from different observing dates are averaged together, supporting the view that these features are real and not detector noise.

Broad features centered at ~1540 Å and ~1604 Å, that are $\Delta\lambda \approx 40$ Å and $\Delta\lambda \approx 20$ Å in width, respectively, are also observed. The feature at 1604 Å is possibly explained as FE III (1601–1611 Å, UV118) or Al III (1600–1612 Å) observed in early O and B stars (Code 1976). Generally, B5 to B7 V stars exhibit weak absorption due to Si IV and C IV (Nandy 1976). As seen here the features at 1400 Å and 1604 Å would be consistent with this interpretation. However, the feature at 1540 Å cannot be attributed to C IV because its measured wavelength (even in low resolution) is too far removed from the rest wavelengths of the resonance doublets (1548 Å, 1550 Å). Furthermore, the width of the 1540 Å feature is such that any model invoking some form of line broadening, i.e., turbulent or rotational, leads to unphysical models.

c) *Ground-based Observations*

Observations that were kindly provided to us by J. B. Oke (private communication) with the 200 inch telescope multichannel scanner of TV Gem taken on 1980 January 25 is shown in Figure 2. Absolute flux measurements taken here between 3200 Å and 10,000 Å clearly show the rapid decline of F_ν with decreasing wavelength and corresponds to the expected emission of an M1 type supergiant. Also present are the H and K Ca II resonance lines at 3968 Å and 3933 Å and TiO molecular bands identified at 5163 Å and 6155 Å consistent with a $T_{\rm eff} \lesssim 3500$ K star. At wavelengths <3600 Å the continuum becomes essentially flat down to 3200 Å, where the sensitivity decreases rapidly.

The absolute flux level measured by Oke at ~3200 Å uncorrected for absorption is $F_\lambda = 2.78 \times 10^{-13}$ ergs cm^{-2} s^{-1} Å^{-1}. The UV continuum flux from our *IUE* data at wavelengths of ~3200 Å (uncorrected for absorption) is $F_\lambda = 2 \times 10^{-13}$ ergs cm^{-2} s^{-1} Å^{-1}. This ground-based observation confirms our results with *IUE* and supports the UV flux estimates that we have derived from our data because flux estimates at wavelengths where both sets of data overlap show agreement within a factor of 2. We estimate that approximately 40% of the continuum flux at 3000 Å is contributed by the M1 supergiant. At wavelengths $\gtrsim 3200$ Å the continuum emission is essentially due to the M1 supergiant. At wavelengths $\lesssim 3200$ Å the continuum is dominated by the hot companion and explains why this spectral characteristic of TV Gem was not recognized prior to our UV satellite data.

IV. INTERPRETATION OF RESULTS

Comparing the general properties of the UV continuum in the short wavelength range with *OAO 2* spectra of standard early-type stars, we find that the continuum might be explained if the companion is a B9–A1 (III–IV) star, although the lack of C IV (1550 Å) is inconsistent with this assumption (Nandy 1976). An O or B supergiant is immediately ruled out because such a star would be sufficiently luminous that earlier spectral classification observations of Keenan (1942), Eggen (1967), and Morgan and Keenan (1973) would have detected its presence. On the other extreme, a

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1980ApJ...241..774M

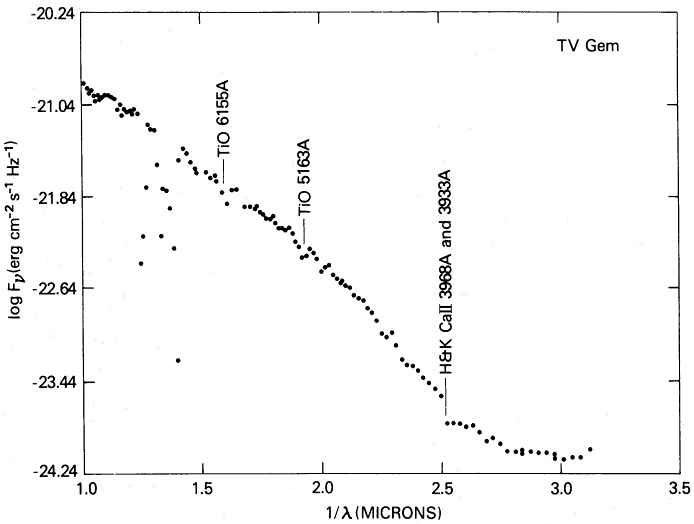

FIG. 2.—Multichannel scanner spectrum of TV Gem obtained by J. B. Oke on 1980 January 25 on the 200 inch telescope. The rapidly decreasing continuum with decreasing wavelength is expected for an M1 supergiant. TiO bands typical of cools stars are present and their strength is consistent with an M1 spectral designation. Below 3600 Å the continuum is dominated by the hot companion. The measured flux from these data at 3200 Å agrees within a factor 2 with *IUE* calibrated flux estimates.

bright white dwarf or central star of a planetary nebula is also ruled out because the expected UV continuum flux based on stellar parameters of Allen (1973) would be $\sim 10^2$ times less than observed for a star at 1400 pc.

Based on the adopted distance to TV Gem a B9 III–IV star would have an apparent magnitude uncorrected for absorption $m_V = 10.35$ (absorption corrected $m_V = 9.15$), and corresponding absolute magnitude $M_V = -2.8$ and bolometric magnitude $M_{\rm bol} = -3.4$. Similarly, an A1 III–IV type would have $m_V = 9.8$ uncorrected for absorption (absorption corrected $m_V = 8.6$) and $M_V = -2.8$ and $M_{\rm bol} = -3.1$.

From Crawford *et al.* (1955) the absolute magnitude of TV Gem is $M_V = -5.7$ and from Humphreys (1970) the apparent magnitude corrected for absorption is $m_v = 6.58$. Accordingly, if we postulate the existence of a B9 or A1 III–IV type star, the difference in apparent magnitude between the two stars is 2 to 3 magnitudes. Although the M1 supergiant is brighter than a B9 or A1 star by approximately 3 magnitudes, one would expect that some level of flux contribution to the photometric color of the M1 be made by an early companion, especially in the blue band. Humphreys (1970) finds for TV Gem a $B-V = +2.30$ and from Lee (1970) we find $B-V = +2.25$, that is consistent with a normal M1 supergiant. For comparison an M1 supergiant similar to TV Gem such as α Sco (M1 Iab+B), but known to have an early companion, has a $B-V = +1.82$ (Lee 1970). The difference in magnitudes between primary and secondary in α Sco is $\Delta M \gtrsim 4$. Accordingly, the $B-V$ color index of TV Gem does not indicate an abnormally high level of blue continuum but in fact suggests a color typical of only a cool star, even though the estimated magnitude difference between primary and secondary is $\Delta M \approx 3$. The $B-V$ in TV Gem should in fact be even smaller than that measured for α Sco on the basis of this analysis.

An observational test to determine if in fact an early companion is associated with TV Gem would consist of a *UBV* monitoring program. TV Gem has a variable designation SRc (Kukarkin *et al.* 1969) and, as such, has irregular excursions in luminosity that occur on time scales of 182 days. If the companion is assumed to have constant brightness, the $B-V$ color index of TV Gem should become smaller as the M supergiant approaches minimum light. If a correlation is established between color and brightness in the manner described here, this would argue in favor of the presence of a early companion star.

An alternative explanation of our *IUE* data might be found if we consider the presence of a high energy source in close proximity to the extended envelope of the M1 supergiant. If $F_\lambda \propto \lambda^0$ or even $F_\lambda \propto \lambda^{-1}$ then $F_\nu \propto \nu^{-2}$ and $F_\nu \propto \nu^{-1}$, respectively. This frequency dependence is similar to the properties of the high energy spectrum in soft X-rays observed in well known X-ray sources (Dolan *et al.* 1977; Dolan *et al.* 1979). Emission from an accretion disk onto a compact object may thus explain the strong UV continuum. This interpretation immediately explains the general absence of blue excess in the spectrum of TV Gem and an absence of strong or weak emission lines. As such, an accretion disc could form from the material exchanged from the extended envelope of the primary that falls on a condensed object that would heat infalling material to temperatures in the 10^6 K range. Accordingly, soft X-ray observations obtained with *HEAO 2* (*Einstein*) satellite using the Image Proportional Counter would prove very useful in determining the nature of the companion of TV Gem.

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1980ApJ...241..774M

Above 1 KeV (the estimated absorption at 1400 pc) we require a column density in our line of sight $N_{\rm H\,I} \approx 5 \times 10^{21}$ cm^{-2} in order to reduce the soft X-ray flux by a factor $1/e$. Our column density estimates discussed previously in connection with UV extinction is $N_{\rm H\,I} \approx 2 \times 10^{21}$ cm^{-2}. As such, the soft X-ray absorption in the 1–5 KeV energy range is small. We find that an accretion disk with a temperature of $\sim 10^6$ K would produce a flux at the detector in the 1–5 KeV range of $\sim 10^{-12}$ ergs cm^{-2} s^{-1}, which is within the spectral sensitivity range of the Image Proportional Counter (IPC) on *HEAO 2* and detectable with suitably long exposures of $\sim$3 hours. Therefore, TV Gem would be a prime candidate for soft X-ray observations because even a null result would narrow our choice of possible interpretations.

Further *IUE* observations are required in high dispersion in order to positively identify the absorption features detected in low resolution. Exposures of 8–10 hours would be adequate to obtain reasonable signal to noise spectra. Work in the UV and soft X-ray range is proceeding.

V. SUMMARY

Strong UV continuum has been detected between 1200 Å and 3200 Å from the luminous M1 Iab supergiant TV Gem. Broad absorption features centered at 1368 Å, 1400 Å, 1540 Å, and 1604 Å characterize the short wavelength spectrum. The feature at approximately 1400 Å is possibly attributed to line blends of Si IV, which is characteristic of features observed in early B type stars. The 1604 Å feature is possibly attributed to Fe III or Al III. However, a feature of comparable strength to those observed at 1400 Å and 1604 Å centered at 1540 Å cannot be identified. The UV continuum is possibly explained by a B9 or A1 III–IV early companion that would have an estimated brightness approximately 2 to 3 magnitudes fainter than the M1 supergiant. However, published $B-V$ data of TV Gem do not indicate an enhancement or blue excess in the continuum of this M supergiant. Ground-based observations obtained with the multichannel scanner on the 200 inch telescope by J. B. Oke (private communication) confirms a strong blue continuum at wavelengths <3600 Å, where the emission from the cool M1 star does not dominate the integrated light.

It is suggested that the UV continuum observed with *IUE* is explained by an accretion disk formed by mass transfer from the extended envelope of the M1 primary onto the surface of a highly condensed secondary star. Soft X-ray observations are suggested in order to investigate this interpretation of our UV observations. Monitoring the $B-V$ color index of the M1 star over the irregular light cycle of the supergiant (approximately 182 days) in order to establish a possible correlation between color index and intrinsic luminosity of the supergiant would also be important in defining the nature of the companion.

We thank the resident astronomers on *IUE* for assistance in data acquisition. We also thank Dr. Bidelman for helpful information concerning background data on TV Gem and for obtaining a spectrum of this star. Drs. Klingelsmith and Fahey provided computer software for reducing data. Dr. Wayne Warren provided useful background information. In particular, we thank Dr. Oke for obtaining ground-based spectra of this star and Dr. Greenstein for useful discussions and assistance in obtaining data from the multichannel scanner.

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