

## EVIDENCE FOR A COMPANION TO BM GEM, A SILICATE CARBON STAR<sup>1</sup>

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### ABSTRACT

Balmer and Paschen continuum emission, as well as Balmer series lines of P Cygni–type profile from  $H\gamma$  through  $H_{23}$ , are revealed in the violet spectra of BM Gem, a carbon star associated with an oxygen-rich circumstellar shell (“silicate carbon star”). The blueshifted absorption in the Balmer lines indicates the presence of an outflow, the line-of-sight velocity of which is at least  $400 \text{ km s}^{-1}$ . The Balmer lines show a significant change in profile over a period of 75 days. We argue that the observed unusual features in BM Gem are strong evidence for the presence of a companion, which should form an accretion disk that gives rise to both an ionized gas region and a high-velocity variable outflow. The estimated luminosity of  $\sim 0.2$  ( $0.03\text{--}0.6$ )  $L_{\odot}$  for the ionized gas can be maintained by a mass accretion rate for a dwarf companion of  $\sim 10^{-8} M_{\odot} \text{ yr}^{-1}$ , while  $\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$  is sufficient for accretion to a white dwarf companion. These accretion rates are feasible for some detached binary configurations on the basis of the Bondi-Hoyle–type accretion process. Therefore, we conclude that the carbon star BM Gem is in a detached binary system with a companion of low mass and low luminosity. However, we are unable to determine whether this companion object is a dwarf or a white dwarf, although the gas outflow velocity of  $400 \text{ km s}^{-1}$ , as well as the nondetection in the X-ray survey, favor its identity as a dwarf star. The upper limits for binary separation are 210 and 930 AU for a dwarf and a white dwarf, respectively, in the case of circular orbit. We also note that the observed features of BM Gem mimic those of Mira (*o* Cet), which may suggest actual similarities in their binary configurations and circumstellar structures.

*Subject headings:* stars: AGB and post-AGB — stars: carbon — stars: evolution —

stars: individual (BM Geminorum, EU Andromedae, V778 Cygni, Y Canum Venaticorum) —

stars: mass loss — stars: winds, outflows

### 1. INTRODUCTION

When low- and intermediate-mass stars evolve along the asymptotic giant branch where double shell burning of He and H takes place in the interior, the He burning becomes unstable and gives rise to periodic thermonuclear runaway (“thermal pulse” or “He shell flash”), which induces mixing of newly synthesized  $^{12}\text{C}$  and other processed materials at the surface (third dredge-up; Iben 1975; Sugimoto & Nomoto 1975). The mixing gradually enhances the surface abundance of carbon, which will eventually turn a star originally oxygen-rich in the surface chemical composition into a carbon star (e.g., Iben & Renzini 1983).

Among cool luminous carbon stars, there are a group of stars that show silicate dust emission features in the mid-infrared at 10 and  $18 \mu\text{m}$  (Little-Marenin 1986; Willems & de Jong 1986); these are the so-called silicate carbon stars. Silicates contain the

signature of oxygen-rich chemistry in their circumstellar dust shells, while their optical spectra, dominated by molecular absorption bands of  $\text{C}_2$  and CN, show that their atmospheres are carbon-rich. The oxygen-rich chemistry in their circumstellar envelopes is also confirmed in the gas phase by the detection of water vapor masers at 22 GHz (Benson & Little-Marenin 1987; Nakada et al. 1987). Even carbon-rich objects showing crystalline silicate features have been discovered (Waters et al. 1998; Molster et al. 2001).

The intriguing coexistence of oxygen-rich and carbon-rich chemistries in a single system prompted two hypothetical explanations. One was a binary system consisting of a carbon star and a dust-enshrouded M-type giant (OH/IR) star (Benson & Little-Marenin 1987; Little-Marenin et al. 1988). The other was more interesting, i.e., that we are witnessing a brief evolutionary stage where the star is in transition from an oxygen-rich star to a carbon star by the third dredge-up while the remnant oxygen-rich dust shell is still visible (Willems & de Jong 1986, 1988). These earlier pictures were, however, discarded based on the absence of both spectroscopic signatures of a luminous M-type (OH/IR) companion (Noguchi et al. 1990; Lambert et al. 1990) and variability of the color indices and silicate features (Chan & Kwok 1988; Lloyd-Evans 1990), as well as a stringent requirement that the primary and secondary must have very similar masses (Lambert et al. 1990). Near-infrared speckle interferometry, as well as water maser monitoring, also ruled out the presence of a luminous M-type companion to the primary carbon star (Engels & Leinert 1994) among silicate carbon stars.

Morris (1987) suggested that a binary system of a mass-losing red giant star and either a main-sequence dwarf or a white dwarf companion can develop an accretion disk around the companion, sometimes a circumbinary disk or even a circumprimary disk,

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TABLE 1  
OBSERVATION SUMMARY

Name	R.A. (J2000.0)	Decl. (J2000.0)	Exp. (s)	Res. ( $\lambda/\Delta\lambda$ )	Date (UT)	S/N (at 4000 Å)
BM Gem .....	07 20 58.9	+25 00 07.28	3600	50000	2001 Jan 29	~15
			1800	50000	2001 Apr 14	~15
V778 Cyg.....	20 36 07.4	+60 05 26.2	2400	38000	2001 Jul 30	<1
EU And.....	23 19 58.2	+47 14 28.0	2400	38000	2001 Jul 30	<1
Y CVn.....	12 45 07.8	+45 26 24.9	900	50000	2001 Feb 1	~1
Feige 34 .....	10 39 36.7	+43 06 09.3	300	9000	2001 Jan 28	~80

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

depending on the system configuration. Lloyd-Evans (1990) was inspired by Morris's picture to propose that in silicate carbon stars the oxygen-rich material accumulated in a disk around a hypothetical companion when the primary was an oxygen-rich mass-losing star which later turned into a carbon star through the third dredge-up. This picture reconciles the observed red infrared color and the relatively small extinction in the optical. The disk should be somewhat thickened and may extend to the circumbinary region to provide a sufficient mid-infrared flux. Engels & Leinert (1994) inferred for V778 Cyg and EU And a minimum radius of the molecular reservoir where water masers reside of  $45 \sin i$  AU, where  $i$  denotes the inclination of the reservoir, which is  $90^\circ$  when seen edge-on, based on the assumed mass of  $1 M_\odot$  for the primary, Keplerian motion for the maser components, and the constancy of radial velocities of the maser lines. Kahane et al. (1998) and Jura & Kahane (1999) proposed the existence of a circumbinary reservoir in Keplerian motion in the silicate carbon stars BM Gem and EU And on the basis of the detection of CO  $J = 1-0$  and  $J = 2-1$  emission with very narrow widths at their systemic velocities. They suggested that the silicate grains reside in the reservoir, which was presumably built by the influence of a postulated unseen companion when the primary was an oxygen-rich giant. Waters et al. (1998) noted the similarity to silicate carbon stars of the Red Rectangle, which possesses a circumbinary disk showing crystalline silicate features, an extended carbon-rich outflow, and narrow CO emission lines. However, Yamamura et al. (2000) suggested a picture similar to that reported by Lloyd-Evans (1990) based on analysis of the *ISO* spectrum of another silicate carbon star, V778 Cyg. They found that dust grains in the circumbinary region where the grains can be warm enough to emit silicate features will be blown out in less than one orbital period, and thus unable to form a circumbinary reservoir. They concluded that the source of the silicate features must be the oxygen-rich material continuously blown out from the disk around a companion by the primary's wind and radiation pressure.

The above scenarios all postulate a low-mass, low-luminosity companion, although no observational evidence has yet been provided. To gain further understanding of silicate carbon stars, it is essential to determine whether they indeed have a companion star. It would be very difficult, however, to detect a postulated low-luminosity companion in the optical or longer wavelength bands because the primary carbon star must outshine the companion by many orders of magnitude in these wavelength regions. In this respect, it has long been known that cool carbon stars exhibit extreme violet flux deficiency (Shane 1928), the agent of which has not yet been unambiguously identified (the "violet opacity problem"). Indeed, cool carbon stars are very dim in the violet region; e.g., the  $U - V$  of the carbon star Y CVn is 8.9 (Nicolet 1978), while those of M5 giants and dwarfs are 4.2 and 2.8, respectively (Allen 1976). This phenomenon can be exploited to

search for signatures of companions to silicate carbon stars in the violet spectral region. Therefore, we performed high-sensitivity spectroscopic observations of the visually brightest silicate carbon stars, BM Gem, V778 Cyg, and EU And, in the violet spectral region. While we saw no significant violet emission in V778 Cyg or EU And, we detected a featureless continuum below 4000 Å in BM Gem, where the Balmer continuum is higher than the Paschen continuum at the Balmer limit, which is very unusual for a cool luminous carbon star. In addition, the Balmer series lines were traced from  $H\gamma$  up to  $H_{23}$ , and they showed distinct P Cygni-type profiles. The profiles give a gas expansion velocity of at least  $400 \text{ km s}^{-1}$ . Such a high-velocity outflow has never been observed in any type of currently mass-losing carbon star. Additional observations 75 days later further revealed considerable time variability of the Balmer lines. In addition, the BM Gem system was found to be similar to the Mira (*o* Cet) system, which is the prototype of a binary system consisting of a luminous AGB star (Mira A) and a low-mass, low-luminosity companion (Mira B). In the following sections we discuss the origin of the continuum emission and the P Cygni-type Balmer lines and argue for the presence of a companion to BM Gem.

## 2. OBSERVATIONS

Observations of BM Gem, the brightest silicate carbon star in the visual region, were made with the High Dispersion Spectrograph (HDS; Noguchi et al. 2002) at the Nasmyth focus of the Subaru Telescope (Kaifu et al. 2000; Iye et al. 2004) on 2001 January 29 and April 14. We used the atmospheric dispersion corrector for the optical Nasmyth focus. The entrance slit width was set to  $360 \mu\text{m}$  ( $0.72''$ ), which corresponded to a resolution of  $\sim 50,000$ . A quartz glass filter was inserted behind the slit. The HDS is equipped with two mosaicked CCDs from EEV with  $2048 \times 4100$  pixels of  $13.5 \mu\text{m}$  square. We used the 250 grooves  $\text{mm}^{-1}$  cross-disperser grating to observe the range between 3550 and 5200 Å (3550–4350 and 4400–5200 Å). We made two 30 minute exposures and one 30 minute exposure in January and April, respectively. For comparison, a bright J-type carbon star, Y CVn, was also observed for 15 minutes on 2001 February 1 (UT) with the same settings, because all the silicate carbon stars examined spectroscopically were known to be J-type stars (Lloyd-Evans 1990), which have low  $^{12}\text{C}/^{13}\text{C}$  abundance ratios ( $\lesssim 10$ ) in the atmosphere (Bouigue 1954). We also observed the second- and third-brightest silicate carbon stars, V778 Cyg and EU And, for 40 minutes each on 2001 July 30 with almost the same settings, but we employed a slit width of  $1.0''$  and  $2 \times 2$  binning for the CCD readout to attain as high a signal-to-noise ratio (S/N) as possible, which gave an effective spectral resolution of  $\sim 38,000$ . A summary of the observations is given in Table 1. The last column shows the S/N at around 4000 Å in the reduced one-dimensional spectrum. The photometric and astrometric data of

TABLE 2  
ASTROMETRIC AND PHOTOMETRIC DATA

Name (1)	$\pi$ (mas) (2)	$\sigma_\pi$ (mas) (3)	$B$ (4)	$V$ (5)	$I$ (6)	$J$ (7)	$H$ (8)	$K$ (9)	$L$ (10)
BM Gem .....	1.83	1.24	10.72	8.40	4.96	4.28	3.32	2.75	2.47
V778 Cyg.....	...	...	13.75	10.26	...	5.25	4.20	3.54	3.18
EU And.....	...	...	13.70	10.47	...	5.41	4.37	3.79	3.33
Y CVn.....	4.59	0.73	8.41	5.42	1.25	0.59	-0.37	-0.89	-1.42

the targets taken from the literature are summarized in Table 2. Columns (2) and (3) show the *Hipparcos* parallax and its uncertainty (ESA 1997), respectively. Near-infrared data in columns (6)–(10) are from Noguchi et al. (1981) for BM Gem and Y CVn and from Noguchi et al. (1990) for V778 Cyg and EU And. The  $B$  and  $V$  magnitudes are from the *Hipparcos* and Tycho catalogs (ESA 1997) for BM Gem and Y CVn and from Alksnis & Žaice (1993) for V778 Cyg and EU And. Data reduction was performed using the echelle package from NOAO IRAF.<sup>10</sup> Standard procedures were followed: bias subtraction, flat-fielding, scattered light subtraction, extraction of one-dimensional spectra, dispersion correction by Th-Ar lamp spectra, and removal of the echelle blaze profile by continuum lamp spectra. Strong cosmic-ray events were removed manually.

We detected significant emission in BM Gem throughout the observed wavelength range. We then attempted to apply flux calibration to the observed spectra of BM Gem. The star Feige 34, observed on 2001 January 28 under  $\sim 0.6''$  seeing with  $4.0''$  slit width to let virtually all the incident light enter the spectrograph, was used for our approximate flux calibration. We derived the system response from the observed spectra of this hot white dwarf. We applied an atmospheric extinction correction based on the Mauna Kea extinction curve (Beland et al. 1988) to the spectra and compared them with the calibrated magnitudes at  $50 \text{ \AA}$  intervals of Feige 34 prepared in IRAF, which is based on Massey et al. (1988). We then corrected the spectra of BM Gem for the atmospheric extinction and system response. Finally, we applied a correction for light losses from the entrance slit due to seeing. Seeing size was measured to be  $0.80''$  and  $0.85''$  for the January and April observations, respectively. We approximated the seeing image by a single Gaussian and obtained values of 0.71 and 0.68 for the slit transmission efficiency for January and April, respectively, against a  $0.72''$  slit width assuming perfect telescope guiding. The spectra of Y CVn were also calibrated in the same manner for comparison. The seeing size at the observation of Y CVn was  $0.80''$ , which gave a slit efficiency of 0.71.

The uncertainty in the absolute flux densities thus obtained is nonnegligible because the data were taken on different nights with somewhat different seeings with a slit width close to the size of the seeing image, a flux standard was observed on only one night, and the violet region is near the atmospheric cutoff, which is sensitive to extinction corrections. The uncertainty due to seeing and guiding, which applies to BM Gem, is estimated to be  $\pm 0.25$  mag in each spectrum, adopting maximum possible errors of  $0.2''$  in both seeing estimate and guiding. The uncertainty in the extinction correction which applies to both BM Gem and Feige 34 can give rise to an underestimate in their brightness of about 0.2 mag. It is obtained by assuming the employed extinction

coefficient of  $0.37 \text{ mag air mass}^{-1}$  at  $3600 \text{ \AA}$  (Beland et al. 1988), with smaller values for longer wavelengths, and was subject to a possible increase of 50%, although all our observations were made under clear sky conditions and the air masses were only 1.01, 1.20, and 1.10 for BM Gem (January), BM Gem (April), and Feige 34, respectively. Taking all these uncertainties into account, each flux density derived is likely to be accompanied by an uncertainty range of  $(-0.45, +0.25)$ , while the relative uncertainty between BM Gem (April) and BM Gem (January) can be as large as  $0.7 (= 0.25+0.25+0.2)$ . Any difference between the two observations smaller than this magnitude is dominated by a calibration error and should be treated as insignificant.

We did not apply the above flux calibration to either V778 Cyg or EU And because we did not see any significant emission in the region shortward of  $4000 \text{ \AA}$ . These stars are 3 mag fainter than BM Gem in  $B$  (Table 2). If we put BM Gem farther away from us so that its  $B$  becomes 3 mag fainter, then any signal of the violet continuum on the raw CCD image becomes only one-quarter or less of the CCD read noise and merely equal to it or even less in the case of  $2 \times 2$  binning. Then, the nondetection of the violet continua here in V778 Cyg and EU And indicates that they are not as bright as that of BM Gem for their  $B$  magnitudes. Nevertheless, it does not necessarily mean that they do not have a similar violet continuum. It is necessary to achieve much higher sensitivities for V778 Cyg and EU And to distinguish between the presence and absence of a continuum like that in BM Gem. We do not discuss the violet spectra of V778 Cyg or EU And further in this paper.

The observed spectrum was corrected for the Doppler shift and transformed to the wavelength scale with respect to the local standard of rest (LSR) using the tasks `rvcorrect` and `dopcor` in IRAF. The stellar systemic velocity with respect to LSR was also subtracted in the final spectra shown in this paper. Thus, matter stationary to the center of mass of the system should appear at zero velocity. We employed the systemic velocity of  $73.2 \text{ km s}^{-1}$  ( $V_{\text{LSR}}$ ) for BM Gem based on millimeter-wave CO emission lines (Kahane et al. 1998; Jura & Kahane 1999). This is in agreement with the  $V_{\text{LSR}}$  of  $74.7 \text{ km s}^{-1}$  derived from the heliocentric radial velocity of  $85.3 \pm 0.4 \text{ km s}^{-1}$  obtained for the CO first-overtone bands by Lambert et al. (1990). For Y CVn, we used  $21.2 \text{ km s}^{-1}$ , based on the millimeter-wave CO  $J = 1-0$  emission (Izumiura et al. 1995), as the systemic velocity with respect to LSR. It should be noted that radial velocities of the observed spectral lines given below will carry a typical uncertainty of  $\sim 0.5 \text{ km s}^{-1}$  on the basis of the observed line widths and strengths, achieved S/N, and employed spectral resolution.

### 3. RESULTS

#### 3.1. Violet Spectra of BM Gem

The resulting spectra of BM Gem taken with the CCD that observes the shorter wavelength portion, reduced to a resolution

<sup>10</sup> IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

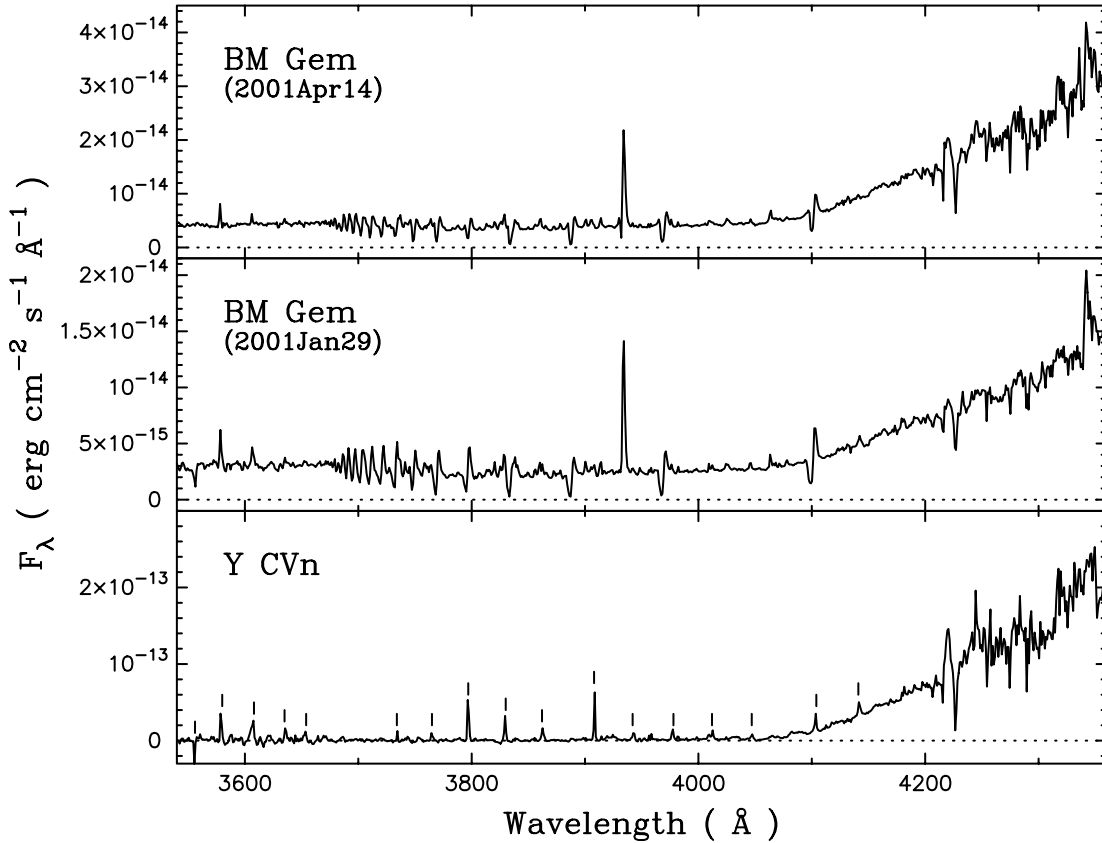


FIG. 1.— Violet spectra of a silicate carbon star, BM Gem, on 2001 January 29 and April 14 and a prototypical J-type carbon star, Y CVn. All the spectra are binned to steps of 1 Å. The dotted line indicates the zero level. Note the significant continuum emission, Balmer lines, and Ca II K emission in BM Gem. The small difference in the continuum level is probably due to the measurement uncertainty (see text for details). Vertical tick marks in the bottom panel give the positions of artifacts due to strong red light contamination, which is also present in BM Gem but is not prominent because of the strong continuum (see text for details).

of 1 Å, are shown in Figure 1, along with those of Y CVn. We have adjusted the vertical scales so that the slopes of the spectra between 4050 and 4200 Å look similar to one another. The spectra of BM Gem show significant Balmer and Paschen continuum emission in the violet region, which is evident when compared with Y CVn, which shows no detectable violet continuum. What is more intriguing is that the level of the Balmer continuum is 1.3 times higher than that of the Paschen continuum when compared around the Balmer limit in both observation occasions. This indicates that the continuum emission comes from an ionized gas region. The spectra also show a series of emission lines that are identified with hydrogen Balmer series lines from H $\gamma$  through H $_{23}$ . Moreover, the Balmer lines show P Cygni–type line profiles, suggesting the presence of an outflow being accelerated outward against the central continuum source. H $\beta$  emission was not identified at all in our spectra recorded on the CCD that covers the longer wavelength part, probably because the spectral range is dominated by the strong carbon star spectra. Broad Ca II K emission with a blueward depression was also detected, but Ca II H emission was absent. The Ca II H emission could be absorbed by the hydrogen in the outflow, because the expected wavelength range of the Ca II H line (3968.470 Å; Moore 1959) coincides with the absorption core of the P Cygni profile of the H $\epsilon$  line (3970.074 Å; Moore 1959). Note that the features that mimic emission lines (Fig. 1, vertical tick marks) seen shortward of 4150 Å in Y CVn are contamination by ghost spectra of the very strong red light of the star, probably due to the cross-disperser grating. The same ghost features are also present in the spectra of BM Gem at the same positions, where only H $_{10}$  of the Balmer lines is significantly contaminated.

The fluxes per unit wavelength at wavelength  $\lambda$ ,  $F_\lambda$ , of the Balmer continuum of BM Gem after the approximate flux calibration in § 2 are  $3.0 \times 10^{-15}$  erg cm $^{-2}$  s $^{-1}$  Å $^{-1}$  in the January spectra and  $4.3 \times 10^{-15}$  erg cm $^{-2}$  s $^{-1}$  Å $^{-1}$  in the April spectra immediately shortward of the Balmer limit at 3646 Å. These correspond to 16.1 and 15.7 mag following the definition of  $m \equiv -2.5 \log F_\nu - 48.59$ , where  $m$  is the magnitude,  $\nu$  is the frequency, and  $F_\nu$  is the flux per unit frequency at  $\nu$  in erg cm $^{-2}$  s $^{-1}$  Hz $^{-1}$ . Here,  $F_\nu$  is calculated by  $F_\nu = F_\lambda |d\lambda/d\nu| = c\nu^{-2} F_\lambda$  (i.e.,  $\nu F_\nu = \lambda F_\lambda$ ), where  $c$  is the speed of light. This definition gives 0.048 for the magnitude of Vega at 5556 Å (Hayes & Latham 1975). The apparent difference in the continuum level of 0.4 mag is not significant, considering the possible uncertainty of 0.7 mag given in § 2. Thus, we argue that the continuum level is unchanged and adopt a geometrical mean of the two values,  $3.6 \times 10^{-15}$  erg cm $^{-2}$  s $^{-1}$  Å $^{-1}$ , or 15.9 mag. We take the difference of  $\pm 0.2$  mag between this 15.9 mag and the two direct values as an additional uncertainty. Adding this difference to that given in § 2, the total uncertainty range has a magnitude of (–0.65, +0.45). Similarly, the Paschen continuum at 4000 Å has 16.2 and 15.6 mag in the January and April spectra, respectively, and they give 15.9 and (–0.75, +0.55) in magnitude as the flux level and uncertainty range, respectively. Note, however, that BM Gem shows a light variation of 0.2–0.4 mag in 100 days in the  $B$  and  $V$  bands (Alksnis & Žaime 1993). Whether BM Gem is indeed variable in the violet continuum is an interesting issue for future studies.

In the original high-resolution spectra of BM Gem, CN red system lines between 4830 and 5250 Å give average radial velocities around  $-1$  km s $^{-1}$  with respect to the systemic velocity

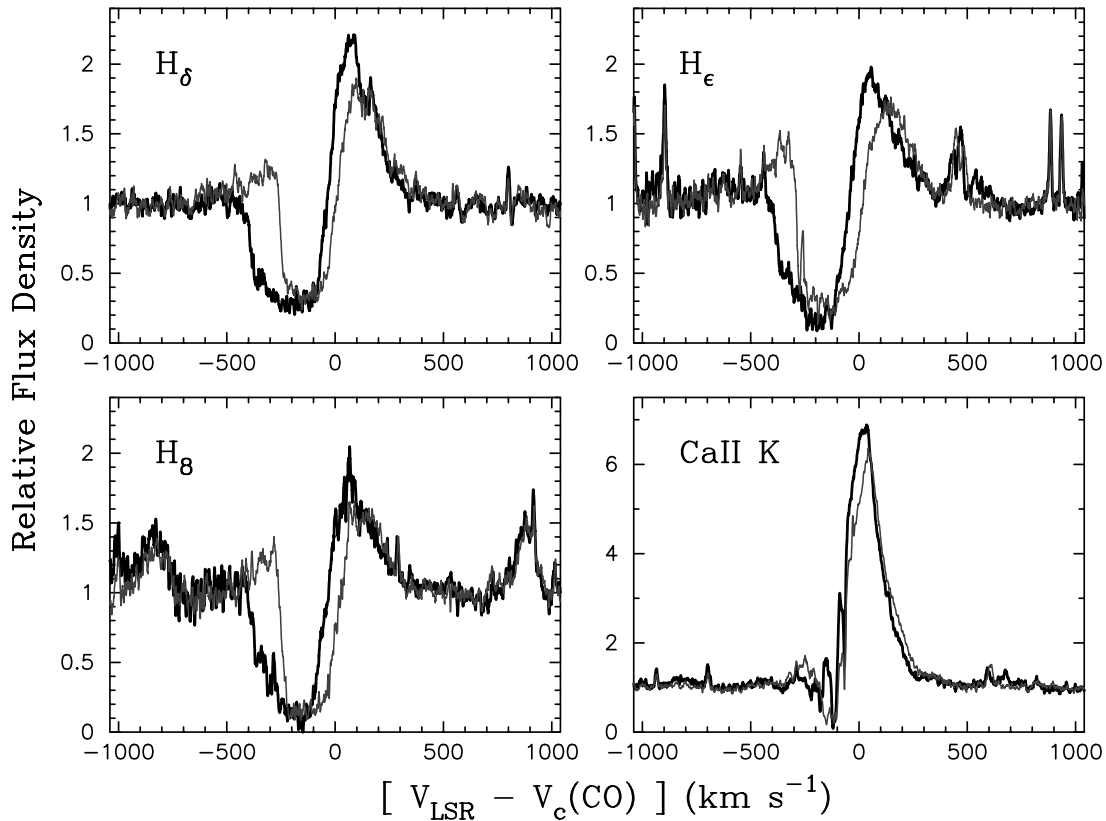


FIG. 2.— $H\delta$  (top left),  $H\epsilon$  (top right),  $H_8$  (bottom left), and  $\text{Ca II K}$  (bottom right) lines in BM Gem observed on 2001 January 29 (thick line) and April 14 (thin line), shown with the original resolution ( $\lambda/\Delta\lambda$ ) of 50,000. The spectra are normalized to the local Paschen continuum. For  $H\delta$  the contribution of the carbon star spectrum was approximately subtracted. The profiles indicate that the gas expansion velocity in January was as large as  $400 \text{ km s}^{-1}$ .

adopted in § 2 in the two observations. Absorption features of the Mn I triplet at  $4030\text{--}4034 \text{ \AA}$  were identified, while low-excitation lines of Ti I were observed in emission shortward of  $4040 \text{ \AA}$ , both of which are typical for late N-type carbon stars, as described by Gilra (1976). The Mn I lines at the two epochs give average radial velocities around  $-6 \text{ km s}^{-1}$ , which are compatible with the millimeter-wave CO outflow velocity of  $7.5 \text{ km s}^{-1}$  and may suggest that they form in the mass-loss flow of the carbon star. The Ti I lines have apparent FWHMs of  $\sim 10 \text{ km s}^{-1}$  and show average radial velocities near  $0 \text{ km s}^{-1}$  in the two observations, suggesting that they originate in the extended atmosphere of the carbon star. The uncertainties in the average radial velocities given above are as large as  $1 \text{ km s}^{-1}$  for the CN red system, Mn I triplet, and Ti I lines. Whether this magnitude of uncertainties, which is slightly larger than the internal uncertainties of  $\sim 0.5 \text{ km s}^{-1}$  given in § 2, is due to their intrinsic variabilities is an issue for future work. The continuum shortward of  $4040 \text{ \AA}$  is almost featureless except for the Balmer and Ti I lines. No absorption features typical of stellar photospheres are seen.

Figure 2 shows higher resolution views of the vicinity of the  $H\delta$ ,  $H\epsilon$ , and  $H_8$  lines together with the Ca II K line observed on the two nights 75 days apart. The zero systemic velocity corresponds to the middle of the P Cygni profile, which argues for the outflowing gas being associated with BM Gem. The line profiles show that the emitting gas, which is likely ionized, is expanding at a velocity as large as  $400 \text{ km s}^{-1}$  in the sight line. This is greater than the highest velocity outflows observed to date in AGB and post-AGB stars V Hya ( $200 \text{ km s}^{-1}$ ; Knapp et al. 1997), CRL 618 ( $200 \text{ km s}^{-1}$ ; Cernicharo et al. 1989), OH 231.8+4.2 ( $330 \text{ km s}^{-1}$ ; Alcolea et al. 1996), and R CrB ( $200\text{--}350 \text{ km s}^{-1}$ ;

Clayton et al. 2003), with the exception of Mira B ( $250$  and  $400 \text{ km s}^{-1}$ ; Wood et al. 2001, 2002) and V854 Cen ( $390 \text{ km s}^{-1}$ ; Clayton et al. 1993). It is, however, much smaller than those of jets seen in symbiotic objects (e.g.,  $\sim 6000 \text{ km s}^{-1}$  in MWC 560; Tomov et al. 1990). In addition, a change in the line shape in each of the Balmer lines over a period of 75 days is evident. The blue edge of the absorption features shifted redward by  $200 \text{ km s}^{-1}$ , while the red edge did so by only  $50 \text{ km s}^{-1}$ .

### 3.2. Energetics of the Violet Emission

Our discoveries of the Balmer and Paschen continua (the former being higher than the latter), the P Cygni-type Balmer series lines, and their line profile variability all suggest that BM Gem is associated with a compact ionized gas region that is accelerated to form a rather spherical, high-velocity outflow. No mechanism is known that allows a single cool luminous carbon star to produce an ionized gas region and a high-velocity outflow. These can, however, be accounted for if we introduce an unseen, low-mass companion that captures matter in the stellar wind from the primary to give rise to an accretion disk. This hypothesis is partially supported by similar spectral features observed in Mira B (*o* Cet B; see § 4), which is a low-mass companion to the AGB star Mira A (*o* Cet A) and is considered to be associated with an accretion disk (Joy 1926, 1954; Deutsch 1958; Warner 1972; Reimers & Cassatella 1985). Low-mass companions with an accretion disk have also been suggested for R CrB stars, which show outflows with similar high velocities and He I lines that require excitation sources (Rao et al. 1999; Clayton et al. 2003).

Formation of an accretion disk has proven to be robust around a companion star to a mass-losing giant in various detached

configurations (Mastrodemos & Morris 1998, 1999). The inner part of the accretion disk must be heated by the released gravitational potential energy from the accreting matter. A hot ionized gas region should form between the innermost region of the disk and the surface of the companion. The accretion phenomenon may also be responsible for the discovered high-velocity variable outflow, although the details of the acceleration mechanism are not yet settled for this type of outflow. Alternatively, the outflow may be due to dust formation in the circumcompanion region, analogous to the scenario proposed for R CrB stars by Clayton (1996). Dust grains would be accelerated through radiation pressure, dragging gas to form the observed high-velocity outflow. The ionization could then be due to collisional ionization in the flow. In this case, to be compatible with the observed broad absorption core that extends from the systemic velocity to the terminal velocity in the P Cygni profile, the ionization must occur before the gas acceleration is completed. Otherwise, the absorber in front of the continuum source has a terminal outflow velocity, and a much narrower absorption component appears near the terminal velocity. In either case (an outflow powered by accretion or driven by radiation pressure on dust grains), the observed spectral features favor the presence of a companion to BM Gem.

The companion should be either a white dwarf or a low-mass dwarf star, because hypotheses invoking a luminous companion have been rejected by previous studies (Noguchi et al. 1990; Lambert et al. 1990; Chan & Kwok 1988; Lloyd-Evans 1990). The gas expansion velocity provides a hint to distinguish the candidates for the companion. White dwarfs have escape velocities on the order of several thousand  $\text{km s}^{-1}$ , while those of low-mass dwarf stars are of the order of several hundred  $\text{km s}^{-1}$ . If gas acceleration occurs near the surface of the secondary and the flow is aligned with the sight line, the latter is the case for BM Gem. However, the former could also be the case if the acceleration takes place at some point distant from the white dwarf, as suggested by Warner (1972), or the flow has a narrow opening angle and is markedly inclined with respect to the sight line. Below, we examine whether such a binary and accretion hypothesis is plausible energetically.

We first attempted to determine the absolute magnitudes of BM Gem at the observed wavelengths by finding the distance to BM Gem. Although it exists, the *Hipparcos* parallax of BM Gem (Table 2) is unreliable. Claussen et al. (1987) gave 1.51 kpc assuming that carbon stars have a constant absolute  $K$ -band magnitude of  $-8.1$ . We made another estimate by comparing the near-infrared flux densities of BM Gem with those of Y CVn, as they are  $^{13}\text{C}$ -rich (J-type) carbon stars resembling each other in spectral characteristics in the optical and near-infrared (Barnbaum et al. 1991; Ohnaka & Tsuji 1999; Yamamura et al. 2000), which may indicate that they have similar intrinsic properties. Y CVn is the only J-type star that has a relatively reliable *Hipparcos* parallax (Table 2) of 218 pc with 16% uncertainty. It is evident from the data shown in Table 2 that the differences between Y CVn and BM Gem in the  $I$  through  $L$  bands are quite constant with a simple mean of 3.72, which indeed shows the two stars to be similar and gives a distance to BM Gem of 1.21 kpc. In addition, the distance of 1.51 kpc reported by Claussen et al. may be reduced to 1.14 kpc, considering that the distance they gave of 0.29 kpc for Y CVn should be readjusted to 0.218 kpc. Hence, we adopted 1.2 kpc with a conservative uncertainty factor of 1.2 as a reasonable estimate for the distance to BM Gem. The total luminosity then becomes  $5.4 \times 10^3 L_{\odot}$  (see Groenewegen et al. 1992), which implies that they are on the AGB even with the distance uncertainty.

Interstellar extinction toward BM Gem ( $l = 193.2^{\circ}$ ,  $b = 17.2^{\circ}$ ) at  $3650 \text{ \AA}$  ( $U$  band),  $A_{3650}$ , is estimated to be at most 0.6 mag. It is obtained by

$$A_{3650} = \alpha N(\text{H I}) [N(\text{H})/E(B - V)]^{-1} [A_V/E(B - V)] (A_{3650}/A_V), \quad (1)$$

where  $N(\text{H I})$  is the column density of atomic neutral hydrogen,  $\alpha$  is a conversion factor from  $N(\text{H I})$  to the total column density of neutral hydrogen  $N(\text{H})$ , including H I and  $\text{H}_2$ ,  $E(B - V) = A_B - A_V$ , and  $A_B$  and  $A_V$  are the extinction at the  $B$  and  $V$  bands, respectively. We take  $N(\text{H I}) = 7 \times 10^{20} \text{ atoms cm}^{-2}$  in the direction of BM Gem from Heiles (1975). Other quantities are found in Cox (2000) and references therein:  $N(\text{H})/E(B - V) = 5.8 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1}$  (Bohlin et al. 1978);  $R_V = A(V)/E(B - V) = 3.1$ , a standard value for diffuse interstellar matter; and  $A_{3650}/A_V = 1.56$  for  $R_V = 3.1$  (Cardelli et al. 1989). Then, we find  $A_{3650} = 0.6\alpha$ , which should be an upper limit because the column density that Heiles (1975) gave is an upper limit to BM Gem, which lies somewhere between the boundary of the H I gas distribution in that direction and us. Since there are no significant molecular clouds found in the direction of BM Gem (e.g., Dame et al. 2001),  $\alpha$  should be close to unity and the use of  $R_V = 3.1$  should be justified. Therefore, we regard  $A_{3650} = 0.6$  as an upper limit. We have also obtained another estimate of  $A_{3650} = 0.3$  for the interstellar extinction toward BM Gem, using  $E(B - V) = 0.067$  from Schlegel et al. (1998) by way of the NASA/IPAC Infrared Science Archive,  $R_V = 3.1$ , and  $A_{3650}/A_V = 1.56$ . This is another upper limit, because BM Gem must lie somewhere between the boundary of the dust distribution in the sight line and us. Taking these into account we adopt the 0.3 mag directly from far-infrared dust observations as a nominal value, the 0.6 mag from the H I observations as a maximum value, and no extinction as a minimum value for  $A_{3650}$  to BM Gem, namely,  $A_{3650} = 0.3 \pm 0.3$ . Then, we find the absolute magnitudes at  $U$  ( $M_U$ ) and  $4000 \text{ \AA}$  ( $M_{4000}$ ) to be  $5.2^{+1.0}_{-1.2}$  and  $5.2^{+1.1}_{-1.3}$ , respectively. These are obtained from the observed magnitudes of  $M_U = 15.9^{+0.45}_{-0.65}$  and  $M_{4000} = 15.9^{+0.55}_{-0.75}$ , the adopted distance of 1.2 kpc, its uncertainty factor of 1.2, and the same interstellar extinction correction of  $-0.3 \pm 0.3 \text{ mag}$  to both of them. The distance and uncertainty factor corresponds to  $-10.4 \pm 0.2 \text{ mag}$ .

The violet continuum is not simply explained by the photosphere of a postulated companion. For the case of a dwarf companion, the probable range of  $M_{4000}$  between  $+6.3$  and  $+3.9$  corresponds to a photosphere with a spectral type between late G and late F, which should show numerous strong absorption lines in the violet region. The violet continuum of BM Gem is, however, featureless except for the  $\text{Ti I}$  emission lines due to the primary carbon star and the Balmer series lines due to the outflow, as mentioned in § 3.1. The featureless continuum requires that the companion's photosphere be smeared by veiling with or without obscuration and contributes only a small fraction of the observed violet continuum. Considering the S/Ns in the original high-resolution spectra of  $\sim 15$ , we should be able to detect absorption lines of which the central depths are as weak as 20% of the continuum level at  $3 \sigma$  confidence. In this violet region, there are many absorption lines with central depths as strong as 80% of the continuum level in late-F through late-K dwarfs. For such strong lines to appear weaker than the  $3 \sigma$  upper limit of 20%, the veiling should be at least 4 times the companion's photosphere. Possible cases are an F- or G-type dwarf obscured by continuous

absorption and covered with veiling and a dwarf later than G type either obscured or not by continuous absorption and covered with veiling. An obscured B- or A-type photosphere is not plausible for the violet continuum, because we do not see the Balmer jump typical for such spectral types and the companion should be less massive than the primary carbon star. The observed violet continuum also cannot be explained by the photosphere of a white dwarf companion, because the  $U$ -band brightness,  $M_U$ , of a DB white dwarf with an effective temperature of 25,000 K is 9.1 (Allen 1976), and those classified as DA and later are less luminous. Therefore, most of the observed violet flux in BM Gem should have an origin other than the photosphere of the assumed companion, which is consistent with our accretion hypothesis.

The total flux of the observed continuum emission  $F^{\text{cont}} = \int_0^\infty F_\nu^{\text{cont}} d\nu$  is approximately obtained by  $\nu_0 F_{\nu_0}^{\text{cont}}$ , where  $\nu$  and  $F_\nu^{\text{cont}}$  mean frequency and the flux of the continuum at  $\nu$  per unit frequency range (flux density) and  $F_{\nu_0}^{\text{cont}}$  and  $\nu_0$  are their typical values. We adopt the frequency at Ly $\alpha$  (1216 Å),  $\nu_{\text{Ly}\alpha}$ , for  $\nu_0$  and the flux density at  $\nu_{\text{Ly}\alpha}$ ,  $F_{\nu_{\text{Ly}\alpha}}^{\text{cont}}$ , for  $F_{\nu_0}^{\text{cont}}$  to obtain  $F^{\text{cont}} \sim \nu_{\text{Ly}\alpha} F_{\nu_{\text{Ly}\alpha}}^{\text{cont}} = \lambda_{\text{Ly}\alpha} F_{\lambda_{\text{Ly}\alpha}}^{\text{cont}}$ , where  $\lambda_{\text{Ly}\alpha}$  is the wavelength of Ly $\alpha$  and  $F_{\lambda_{\text{Ly}\alpha}}^{\text{cont}}$  is the flux of the continuum per unit wavelength range at the Ly $\alpha$  wavelength. Here, we assume  $F_{\lambda_{\text{Ly}\alpha}}^{\text{cont}}$  is approximated by  $F_{\lambda_{\text{BL}}^-}^{\text{cont}}$ , which is the flux of the continuum per unit wavelength range immediately shortward of the Balmer limit at 3646 Å, for which we obtained  $3.6 \times 10^{-15}$  erg cm $^{-2}$  s $^{-1}$  Å $^{-1}$  in § 3.1. These approximations should be valid because model spectra of ionized gas show that the continuum emission diminishes rapidly toward higher frequencies with respect to the Ly $\alpha$  line and because the level of the continuum flux per unit wavelength from ionized gas at the Ly $\alpha$  wavelength is similar to that just shortward in wavelength of the Balmer limit (e.g., Harrington et al. 1981; Pottasch et al. 1981). Then, the product  $\nu_{\text{Ly}\alpha} F_{\nu_{\text{Ly}\alpha}}^{\text{cont}}$  should give a reasonable estimate of the total flux. The above approximations, however, may overestimate the total flux, and another uncertainty of  $(-0, +1)$  in magnitude should be added.

Now, assuming spherical symmetry of the radiation field, the gas radiative luminosity,  $L_g$ , can be estimated as

$$L_g \simeq 4\pi D^2 \nu_{\text{Ly}\alpha} F_{\nu_{\text{Ly}\alpha}}^{\text{cont}} = 8 \times 10^{32} \text{ erg s}^{-1} \sim 0.2 L_\odot, \quad (2)$$

where  $D$  denotes the distance to BM Gem. The total uncertainty range has a magnitude of  $(-1.2, +2.0)$  by summing those discussed previously, or 0.03–0.6  $L_\odot$ . The value of  $L_g$  in this range is always larger than the gas kinematic luminosity,  $(1/2)\dot{m}_{\text{out}}V_e^2$ , and thermal luminosity,  $(3/2)nkT4\pi R^2V_e$ , and dominates the total luminosity as far as  $\dot{m}_{\text{out}} \leq 10^{-9} M_\odot \text{ yr}^{-1}$  and  $T \leq 10^6$  K. Here,  $\dot{m}_{\text{out}}$ ,  $V_e$ , and  $n$  are the mass ejection rate, outflow velocity, and total particle number density, respectively, of the high-velocity outflow. Also,  $k$ ,  $T$ , and  $R$  are the Boltzmann constant, temperature of the gas, and radius under consideration from the center of the outflow source, respectively.

Maximum energy input,  $L_a$ , expected from mass accretion by a companion, is constrained by the gravitational potential energy release from accreting matter, i.e.,

$$L_a = G(M_2\dot{M}_2)/r = 0.16(M_2/0.5)(\dot{M}_2/10^{-10})(r/0.01)^{-1} L_\odot, \quad (3)$$

where  $G$ ,  $\dot{M}_2$ ,  $M_2$ , and  $r$  are the gravitational constant, the companion's mass accretion rate in  $M_\odot \text{ yr}^{-1}$ , its mass in  $M_\odot$ , and its radius in  $R_\odot$ , respectively. In this equation  $M_2/r$  is almost constant and near unity for dwarf stars of type late-F to late-K and is 20–70 for white dwarfs (Allen 1976).

For a white dwarf of  $0.5 M_\odot$  with  $0.01 R_\odot$  (Allen 1976), an accretion rate of  $(0.2\text{--}4) \times 10^{-10} M_\odot \text{ yr}^{-1}$  can afford the observed continuum luminosity of 0.03–0.6  $L_\odot$ , whereas a K5 dwarf of  $0.69 M_\odot$  and  $0.74 R_\odot$  (Allen 1976) can give rise to the observed luminosity when the mass accretion rate is  $(0.1\text{--}2) \times 10^{-8} M_\odot \text{ yr}^{-1}$ . It is not self-evident whether the latter accretion rate is feasible for a dwarf companion in a binary system compatible with the observations, given the current mass-loss rate of  $3 \times 10^{-7} M_\odot \text{ yr}^{-1}$  in BM Gem (Kahane et al. 1998).

According to Warner (1972), the Bondi-Hoyle-type mass accretion rate is written as

$$\begin{aligned} \dot{M}_2 &= (1/2)G^2\dot{M}_1M_2^2 \left[ (v_{\text{rel}}^2 + c_s^2)^{3/2} v_e \right]^{-1} d^{-2} \\ &= 3.4 \times 10^{-9} (\dot{M}_1/10^{-7})(M_2/0.5)^2 \\ &\times \left[ (v_{\text{rel}}^2 + c_s^2)^{3/2} v_e / (7.5)^4 \right]^{-1} (d/30)^{-2} M_\odot \text{ yr}^{-1}, \quad (4) \end{aligned}$$

where  $v_e$ ,  $v_{\text{rel}}$ , and  $c_s$  are the mass outflow velocity from the primary carbon star, relative velocity of the companion to the primary outflow, and speed of sound of the material, respectively, all in km s $^{-1}$ , and  $\dot{M}_1$  and  $d$  are the mass-loss rate of the primary in  $M_\odot \text{ yr}^{-1}$  and binary separation in AU, respectively. Substituting equation (4) in equation (3) we find

$$\begin{aligned} L_a &= (1/2)G^3\dot{M}_1M_2^3 \left[ (v_{\text{rel}}^2 + c_s^2)^{3/2} v_e r d^2 \right]^{-1} \\ &= 5.2 (\dot{M}_1/10^{-7})(M_2/0.5)^3 \left[ (v_{\text{rel}}^2 + c_s^2)^{3/2} v_e / (7.5)^4 \right]^{-1} \\ &\times (d/30)^{-2} (r/0.01)^{-1} L_\odot. \quad (5) \end{aligned}$$

The speed of sound of the material can be neglected here, as it is likely that the wind is flowing supersonically. Here, we may write  $v_{\text{rel}} = (v_e^2 + v_{\text{orbit}}^2)^{1/2}$ , where  $v_{\text{orbit}}$  is the orbital velocity of the companion (Warner 1972; Jura & Helfand 1984).

If we assume that BM Gem is in a binary system consisting of a carbon star of  $1.5 M_\odot$  (Claussen et al. 1987; Groenewegen et al. 1992) and a dwarf of  $0.5 M_\odot$  in a circular orbit with a separation of 30 AU, which is one likely configuration, then the orbital velocity of the companion about the primary becomes 7.7 km s $^{-1}$ . The outflow velocity of the primary carbon star is 7.5 km s $^{-1}$ , and the current mass-loss rate is  $\sim 3 \times 10^{-7} M_\odot \text{ yr}^{-1}$  in BM Gem (Kahane et al. 1998). Then, equation (5) gives an accretion luminosity of 0.08  $L_\odot$ , which is at least compatible with the observed luminosity of BM Gem when its uncertainty range is taken into account. In their smoothed particle hydrodynamic calculations, Mastrodemos & Morris (1999) found that the Bondi-Hoyle accretion is not as efficient as initially thought. The obtained efficiency ( $\dot{M}_2/\dot{M}_1$ ) spreads over a range between 0.1% and 10% for the cases they examined that are compatible with the configurations under consideration here. The efficiencies they found differ not by an order but by a factor from those obtained using equation (4) for the same parameter sets. A dwarf companion is thus at least compatible with the observations.

#### 4. DISCUSSION

In the previous section, we showed that our results were compatible with BM Gem being accompanied by a low-mass, low-luminosity companion with an accretion disk, for which both a main-sequence star and a white dwarf are viable. In this section, we further consider the characteristics of the BM Gem system.

The observed UV-optical (violet) spectral features of BM Gem nearly parallel those of Mira (*o* Cet). Mira is known to consist of

a long-period variable on the AGB, Mira A, and a low-mass, low-luminosity companion separated by about  $0.6''$  ( $\sim 70$  AU), Mira B (Karovska et al. 1997 and references therein). Joy (1926, 1954) reported the first detection of a UV-optical continuum and complex profiles of hydrogen Balmer lines with emission and absorption cores in Mira B. Figure 8 of Reimers & Cassatella (1985) showed that both Balmer and Paschen continua existed, and the level of the former was higher than that of the latter. The Balmer lines were found to be of P Cygni type, and their profiles were shown to be highly variable on a timescale similar to that found for BM Gem (Joy 1926; Yamashita & Maehara 1977), although the lines were not of P Cygni type in Reimers & Cassatella (1985). The P Cygni profiles indicated that the outflow velocity was as large as  $400 \text{ km s}^{-1}$  (Wood et al. 2002). Warner (1972) examined the energetics of Mira B and reported that its total luminosity of  $\sim 0.2 L_{\odot}$  could be accommodated by the Bondi-Hoyle-type accretion of Mira A's wind to Mira B, if the mass-loss rate from Mira A is greater than  $0.8 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$ . The actual mass-loss rate of Mira A is  $\sim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$  (Ryde & Schöier 2001), which supports the Bondi-Hoyle-type accretion. Jura & Helfand (1984) also found the UV-optical luminosity of Mira B to be  $0.2$  ( $0.05$ – $1$ )  $L_{\odot}$ . The above parallels between the spectral features of BM Gem and Mira, as well as the UV-optical luminosity, support the presence of a companion to BM Gem.

Based on the X-ray luminosity, as well as the outflow velocity of  $\sim 400 \text{ km s}^{-1}$ , the companion of BM Gem may not be a white dwarf but a dwarf. Here, we again present a parallel discussion with Mira. A very low X-ray luminosity, which is  $\sim 10^{-3}$  of the UV-optical luminosity, in the Mira system led Jura & Helfand (1984) to conclude that Mira B was not a white dwarf but a dwarf. They argued that the X-ray luminosity would be comparable to the UV-optical luminosity if the companion was a white dwarf. Reimers & Cassatella (1985) noted that there was no direct evidence for the presence of a hot white dwarf companion to Mira A, although they favored a white dwarf companion. Based on a similar discussion, Ireland et al. (2007) recently concluded that Mira B is a K5 dwarf of  $0.7 M_{\odot}$ . If Mira B is indeed a dwarf, then the X-ray luminosity of BM Gem will be as small as that of Mira in the case of a dwarf companion but could be  $10^3$  times as much for a white dwarf companion. Mira has an X-ray photon flux of  $7.6 \times 10^{-3} \text{ counts s}^{-1}$  in the  $0.1$ – $2.4 \text{ keV}$  energy band in the second *ROSAT* source catalog of pointed observations.<sup>11</sup> The X-ray flux from BM Gem in the same energy band could be as much as  $\sim 0.08 \text{ counts s}^{-1}$  for a white dwarf companion, with the difference in their distances of a factor of 10 taken into account. It should have been detected in the *ROSAT* all-sky survey (Voges et al. 1999, 2000), the detection limit of which was about  $0.05 \text{ counts s}^{-1}$ , which is actually not the case. This argues for a dwarf as the companion of BM Gem. However, that both Mira and BM Gem possess a white dwarf companion cannot be excluded completely, because there may exist a mechanism that suppresses the X-ray luminosity arising from the accretion process and one to accelerate the outflow from some distant point from the white dwarf simultaneously. The latter mechanism is favorable for the picture suggested for Mira B by Warner (1972). It is thus difficult to choose exclusively between a dwarf and a white dwarf as the companion, although the data favor a dwarf.

The binary separation of the BM Gem system is only loosely constrained. The separation is found to be  $(0.3$ – $6) \times 10^1 \text{ AU}$  for a dwarf companion, while that for a white dwarf companion is  $(1$ – $5) \times 10^2 \text{ AU}$  to reproduce the observed luminosity of  $0.03$ – $0.6 L_{\odot}$  using equation (5). We adopted  $\dot{M}_1 = 3 \times 10^{-7}$  and  $v_e =$

$7.5$  and assumed that  $M_1 = 1.5$  (the mass of the primary in  $M_{\odot}$ ),  $M_2 = 0.5$ ,  $r = 0.65$  (dwarf) or  $0.016$  (white dwarf), and the system is in a circular orbit. Furthermore, for any combination of  $M_1$  between  $1.0$  and  $2.0$  and  $M_2$  between  $0.3$  and  $1.2$  but  $M_1 > M_2$  (dwarf) or between  $0.3$  and  $0.7$  (white dwarf), there are upper limits of  $210$  and  $930 \text{ AU}$  for a dwarf and a white dwarf companion, respectively, where a realistic  $r$  corresponding to  $M_2$  (Allen 1976; Lang 1999) is used. As equation (3) gives an upper limit and equation (4) is suspected to overestimate the accretion rate (Mastrodemos & Morris 1999), the derived upper limits for the separation are relatively stringent. Mastrodemos & Morris (1999) and Soker & Rappaport (2000) suggested from theoretical considerations that the separation should be  $\lesssim 30 \text{ AU}$  to form an accretion disk around a companion, irrespective of whether it is a dwarf or a white dwarf, in the detached binary configurations under consideration here. The observation that Mira B, which is at least  $70 \text{ AU}$  from Mira A, is associated with an accretion disk despite the moderate mass-loss rate of Mira A of  $\sim 3 \times 10^{-7} M_{\odot} \text{ yr}^{-1}$  suggests that the current hydrodynamic simulations do not constrain the upper limit of the separation very well. As BM Gem has been shown to be a system resembling Mira, its binary separation could be as large as  $70 \text{ AU}$ . Ohnaka et al. (2006) derived an upper limit of  $\sim 60$ – $80 \text{ AU}$  for the diameter of the inner dust-free region in the silicate carbon star IRAS 08002–3803 from mid-infrared interferometry, which at the same time gives an upper limit for the postulated binary separation of  $\sim 80 \text{ AU}$ . However, they suggested that silicate carbon stars with an optically thin dust reservoir, such as BM Gem, have binary separations wider than those of silicate carbon stars with an optically thick reservoir, such as IRAS 08002–3803. In addition, if we pose a constraint that we do not see a Roche lobe overflow, then we find that the binary separation should be larger than  $1.8 \text{ AU}$  for any combination of mass ratio between  $1$  and  $7$  and carbon star radius between  $1$  and  $1.5 \text{ AU}$  using the formulation by Paczyński (1971).

Luminosity of the silicate dust in BM Gem,  $L_d$ , is estimated as

$$\begin{aligned} L_d &= 4\pi D^2 \int F_{\nu}^{\text{silicate}} d\nu \sim 4\pi D^2 (1/5) \nu_{9.7 \mu\text{m}} F_{\nu_{9.7 \mu\text{m}}}^{\text{silicate}} \\ &= 4 \times 10^{35} \text{ erg s}^{-1}, \end{aligned} \quad (6)$$

where  $F_{\nu}^{\text{silicate}}$ ,  $\nu_{9.7 \mu\text{m}}$ , and  $F_{\nu_{9.7 \mu\text{m}}}^{\text{silicate}}$  are the flux density due to silicate dust, frequency at  $9.7 \mu\text{m}$ , and flux density due to silicate dust at the  $9.7 \mu\text{m}$  peak, respectively. We assume that the emission is isotropic and that the feature extends over  $8$ – $12 \mu\text{m}$  and has a flux density of about  $1.2 \times 10^{-11} \text{ W m}^{-2}$  at the peak, which is taken from the IRAS Low-Resolution Spectrograph atlas (Olson et al. 1986). The factor  $1/5$  is a roughly determined correction factor for substituting the integration with the multiplication obtained by a simple calculation of  $(1/2)(12 \mu\text{m} - 8 \mu\text{m})/(9.7 \mu\text{m})$ . The dust luminosity is then  $\sim 110 L_{\odot}$ . The accretion process discussed here cannot be the energy source of the silicate emission lines. The energy must be supplied by the radiation from the primary carbon star of  $\sim 5 \times 10^3 L_{\odot}$  (see § 3.2). The dust luminosity indicates that about 2% of the total stellar luminosity is captured by the dust grains responsible for the silicate features. Barnbaum et al. (1991) found similar values of 1%–2% in BM Gem and V778 Cyg.

It has been speculated that silicate emission features arise from a circumstellar disk around a companion, as well as from a thickened circumbinary disk (Lloyd-Evans 1990). Engels & Leinert (1994) inferred a minimum radius for a circumbinary molecular reservoir of  $45 \sin i \text{ AU}$ , where  $i$  denotes the inclination of the reservoir, which is  $90^{\circ}$  when seen edge-on, for V778 Cyg and

<sup>11</sup> Available at <http://wave.xray.mpe.mpg.de/rosat/tra>.

EU And, assuming a  $1 M_{\odot}$  primary and circular Keplerian motion of the reservoir. They based their inference on constancy better than  $0.06 \text{ km s}^{-1} \text{ yr}^{-1}$  of the radial velocity of the water maser lines. Kahane et al. (1998) and Jura & Kahane (1999) detected a very narrow emission component in the millimeter-wave CO lines in BM Gem and EU And. They interpreted the narrow component as due to a circumbinary reservoir in Keplerian motion formed by some binary interaction with an unseen companion. They argue that the oxygen-rich material responsible for the silicate emission is stored in the long-lived circumbinary reservoir of 100–1000 AU in size, which was formed when the primary star was an oxygen-rich mass-losing star. This picture is further reinforced by the study of the Red Rectangle by Waters et al. (1998), who noted its similarity to silicate carbon stars in that it possesses a circumbinary disk showing crystalline silicate features, an extended carbon-rich outflow, and narrow CO emission lines. The circumbinary reservoir of 100–1000 AU is compatible with both the binary separation of  $(0.3\text{--}6) \times 10^1$  AU (as well as a stringent upper limit of 210 AU) derived for a dwarf companion to BM Gem and the separation of  $(1\text{--}5) \times 10^2$  AU (as well as a stringent upper limit of 930 AU) for a white dwarf companion.

However, Yamamura et al. (2000) found that silicate dust grains responsible for the emission features in V778 Cyg should have temperatures between 600 and 300 K, which implies that their location is between about 25 and 100 AU (12–50 stellar radii) from the primary. They concluded that a circumstellar disk around an invisible companion should be the reservoir of oxygen-rich material, because they found it difficult to locate a circumbinary disk in the vicinity of the companion's orbit. Dust grains there will be swept outward in less than one orbital period by radiation pressure from the primary. They speculated that the silicate features originate from oxygen-rich material continuously blown out by radiation pressure of the primary from the circumcompanion disk that was built when the primary was an oxygen-rich mass-losing star. Furthermore, Ohnaka et al. (2006) suggested that silicate carbon stars may be classified into two groups: one with an optically thick circumbinary dust reservoir with a smaller binary separation, and another with an optically thin dust outflow from the companion's disk with a wider binary separation. Following their criteria, BM Gem belongs to the latter group and thus may show dust outflow from the companion, possibly extending out in a region at 50–100 AU from the primary. Therefore, the region at 30–100 AU is a likely location of the circumstellar molecular/dust reservoir according to both Yamamura et al. and Ohnaka et al. This location is compatible with the binary separation for a dwarf companion but not with the separation for a white dwarf companion.

Finally, it should be noted that all of the silicate carbon stars examined spectroscopically are known to be J-type stars (Lloyd-Evans 1990, 1991), while the opposite is not true. It has been argued that J-type carbon stars are the direct descendants of R-type carbon stars (Lloyd-Evans 1990; Lambert et al. 1990), which form through a mechanism unrelated to the third dredge-up, as both groups of stars are  $^{13}\text{C}$ -rich and lack *s*-process enhancements in their surface chemical compositions (Utsumi 1985; Dominy 1985). Abia & Isern (2000), however, favor another scenario in which the low-mass J-type stars discussed here form via a combination of nonstandard extra mixing and cool bottom processing (Wasserburg et al. 1995) early on the AGB, which is consistent with their luminosities being similar to those of normal cool carbon stars on the AGB (Wallerstein & Knapp 1998; Alksnis et al. 1998). As there seems to be a connection between the J-type nature and the silicate features, the presence of a companion to BM Gem would suggest a possible connection between binarity

and J-type phenomena, which is worth investigating further. Radial velocity monitoring of J-type stars would be important and could be carried out by observing the  $\text{Ti I}$  emission lines in the violet region, as well as numerous photospheric molecular absorption lines.

## 5. CONCLUSIONS

We observed the violet spectra of the three brightest silicate carbon stars, BM Gem, V778 Cyg, and EU And, using the High Dispersion Spectrograph on the Subaru Telescope, and we used a prototypical J-type carbon star, Y CVn, for comparison. Balmer and Paschen continuum emission typical of ionized gas was found to be prominent in the region shortward of  $4000 \text{ \AA}$  in BM Gem, while no significant emission was observed in the same region in V778 Cyg, EU And, or Y CVn. In BM Gem, Balmer series lines were also detected from  $\text{H}\gamma$  through  $\text{H}_{23}$ , and they showed P Cygni-type line profiles. Broad  $\text{Ca II K}$  emission with blueward depression was also found, while the  $\text{Ca II H}$  line is missing, perhaps because it is absorbed by hydrogen in the outflow. The P Cygni profiles give a gas outflow velocity of at least  $400 \text{ km s}^{-1}$ . Such spectral features have not been observed in other cool luminous carbon stars. Furthermore, the P Cygni profiles changed significantly within a period of 75 days, suggesting a compact geometry of the outflow. The overall spectral features mimic those of Mira B. All these features in the cool carbon star BM Gem suggest the presence of a companion that gives rise to an accretion disk, which is responsible for the ionized gas region and the observed high-velocity outflow.

We investigated the energetics of the observed emission assuming a binary system and Bondi-Hoyle-type mass accretion process. The luminosity of the observed continuum emission is estimated to be  $\sim 0.2$  ( $0.03\text{--}0.6$ )  $L_{\odot}$ , while the silicate dust features convey about  $110 L_{\odot}$ , which shows that the silicate dust grains are heated not by the phenomenon discovered here but by radiation from the carbon star. We found that the violet continuum luminosity is accommodated if an accretion rate on the order of  $10^{-8} M_{\odot} \text{ yr}^{-1}$  is achieved for a dwarf companion, while  $10^{-10} M_{\odot} \text{ yr}^{-1}$  is sufficient for a white dwarf companion. Although the required accretion efficiency seems rather high, a main-sequence companion is favored based on the observed outflow velocity of  $400 \text{ km s}^{-1}$  and the nondetection of X-ray flux in the *ROSAT* all-sky survey. The possibility of a white dwarf companion, however, cannot be ruled out, because the outflow could be narrow and inclined with respect to the sight line or accelerated at some distant point from the surface of the white dwarf.

Based on the above findings combined with those of previous studies, we conclude that BM Gem is associated with a low-mass, low-luminosity companion giving rise to an accretion disk. We note that the spectral features and UV-optical luminosity obtained for the BM Gem system closely resemble those of the Mira system, which should represent the actual similarity between the binary configurations of the two systems. We derived the binary separations based on the observed UV-optical luminosity as  $(0.3\text{--}6) \times 10^1$  and  $(1\text{--}5) \times 10^2$  AU for a dwarf and a white dwarf companion, respectively, assuming the primary mass of  $1.5 M_{\odot}$ , companion mass of  $0.5 M_{\odot}$ , circular orbits, and Bondi-Hoyle-type accretion. We also derived another stringent upper limit of the separation of 210 and 930 AU for a dwarf and a white dwarf companion, respectively. The separations for a dwarf are compatible with both the circumcompanion dust reservoir proposed by Yamamura et al. (2000) and Ohnaka et al. (2006) and the circumbinary dust reservoir proposed by Kahane et al. (1998) and Jura & Kahane (1999), while those for a white dwarf are plausible only for the circumbinary reservoir. However, it is still difficult to

choose between the two scenarios for the dust reservoir responsible for the silicate emission features in BM Gem. Very high angular resolution imaging in the ultraviolet would be interesting to depict the reservoir through the violet continuum emission scattered by the silicate grains. If the silicates are located in a circumbinary reservoir, we will see a ringlike structure, while we may see a spiral structure if they are blown out continuously from a circumcompanion disk. It is also important to carry out high-sensitivity, medium-resolution spectroscopy in the ultraviolet of silicate carbon stars other than BM Gem to determine whether the violet spectral features are common among these stars. Theoretical studies of the formation mechanism of the dust reservoir are also required.

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