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Abstract
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Keywords
occultations, plantes and satellites formation, proto-planteary disks, stars, GM Cep, pre-main sequence, Herbig Ae/Be

Disciplines
Other Astrophysics and Astronomy | Stars, Interstellar Medium and the Galaxy

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A Possible Detection of Occultation by a Proto-planetary Clump in GM Cephei

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ABSTRACT

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GM Cep in the young (~ 4 Myr) open cluster Trumpler 37 has been known to be an abrupt variable and to have a circumstellar disk with very active accretion. Our monitoring observations in 2009–2011 revealed the star to show sporadic flare events, each with brightening of $\lesssim 0.5$ mag lasting for days. These brightening events, associated with a color change toward the blue, should originate from an increased accretion activity. Moreover, the star also underwent a brightness drop of ~ 1 mag lasting for about a month, during which the star became bluer when fainter. Such brightness drops seem to have a recurrence time scale of a year, as evidenced in our data and the photometric behavior of GM Cep over a century. Between consecutive drops, the star brightened gradually by about 1 mag and became blue at peak luminosity. We propose that the drop is caused by obscuration of the central star by an orbiting dust concentration. The UX Orionis type of activity in GM Cep therefore exemplifies the disk inhomogeneity process in transition between grain coagulation and planetesimal formation in a young circumstellar disk.

Subject headings: Occultations — Planets and satellites: formation — Protoplanetary disks — Stars: Individual: GM Cep — Stars: pre-main sequence — Stars: variables: T Tauri, Herbig Ae/Be

1. Introduction

The current paradigm suggests that stars are formed in dense molecular cores, and planets are formed, almost contemporaneously with the star, in circumstellar disks. The grain growth process already initiated in the parental molecular cloud continues to produce progressively larger solid bodies. Details are still lacking in how grain coagulation proceeds to eventual planet formation in a turbulent disk. Competing theories include gravitational instability (Safronov 1972; Goldreich, & Ward 1973; Johansen et al. 2007) and planetesimal accretion (Weidenschilling 2000). In any case, density inhomogeneities in the young stellar disk mark the critical first step in the process. Measurements of the fraction of stars with infrared excess—arising from thermal emission by circumstellar dust—indicates a clearing time scale of optically thick disks in less than ~ 10 Myr (Mamajek et al. 2004; Briceño et al. 2007; Hillenbrand 2008). Observationally, this epoch corresponds to pre-main sequence (PMS) stellar evolution from disk-bearing classical T Tauri stars (CTTSs) to weak-lined T Tauri stars with no optically thick disks.

The open cluster Trumpler 37 (Tr 37), at a heliocentric distance of 870 pc (Contreras et al. 2002), is associated with the prominent H II region IC 1396, and is a part of the Cepheus

OB2 association. With a disk frequency of $\sim$ 39% (Mercer et al. 2009), and an age of 1–4 Myr (Marschall, Karshner, & Comins 1990; Patel et al. 1995; Sicilia-Aguilar et al. 2005), Tr 37 serves as a good target to search for and to characterize exoplanets in formation and early evolutionary stages (see Neuhäuser et al. 2011, and references therein on Tr 37).

GM Cep (RA = 21:38:17.3, Dec = +57:31:23, J2000) is a solar type variable in Tr 37. The star has a spectral type of G7 to K0, an estimated mass of 2.1 $M_\odot$ and a radius of 3–6 $R_\odot$ (Sicilia-Aguilar et al. 2008). The youth of GM Cep is exemplified by its emission-line spectrum, prominent infrared excess (Sicilia-Aguilar et al. 2008), and X-ray emission (Mercer et al. 2009), all characteristics of a CTTS. The star has a circumstellar disk (Mercer et al. 2009), with an accretion rate up to 10^{-6} $M_\odot$ yr^{-1}, which is 2–3 orders higher than the median value of the CTTSs in Tr 37 (Sicilia-Aguilar et al. 2006). It is also one of the fastest rotators in the cluster, with $v \sin i \sim 43.2$ km s^{-1} (Sicilia-Aguilar et al. 2008).

Most PMS objects are variables. Herbst et al. (1994) classified such variability into three categories. One class of variation is caused by rotational modulation of cool star spots. Another class of variation arises because of unsteady accretion onto a hot spot on the stellar surface; stars of this type are called EXors, with EX Lupi being the most extreme case. Stars with the third kind of variation, called UX Orionis type variables or UXors, are those which experience variable obscuration by circumstellar dust clumps. About a dozen UXors have been identified so far, with some showing cyclic variability with periods ranging from 8.2 days (Bouvier et al. 2003) to 11.2 years (Grinin et al. 1998).

GM Cep is known to be an abrupt variable, but interpretations on its variability have been controversial. Sicilia-Aguilar et al. (2008) collected photometry of the star from 1952 to 2007 in the literature, supplementing with their own intensive multi-wavelength observations, and suggested GM Cep to be an EXor type variable, i.e., with outbursts and accretion flares. Xiao, Kroll, & Henden (2010) measured archival plates taken between 1895 and 1993, and concluded otherwise—that the variability in the century-long light curve is dominated by dips (possibly from extinction) superposed on quiescent states. If this is the case, GM Cep should be a UXor type variable, as claimed also by Semkov & Peneva (2011).

GM Cep has been observed by the Young Exoplanet Transit Initiative (YETI) collaboration, a network of small telescopes in different longitude zones (Neuhäuser et al. 2011). In addition to the YETI data, the observations reported here also included those collected during non-YETI campaign time, by the SLT 40-cm telescope at Lulin in Taiwan, the Tenagra II 81-cm telescope, in Arizona, USA, the Jena University Observatory 25 cm and 90/60 cm telescopes in Germany, and the 1.5 m telescope of Moleitai Observatory in Lithuania. For the list of YETI telescope and instrument parameters, please refer to Neuhäuser et al. (2011). While the primary goal of the YETI campaigns, each with uninterrupted monitoring of a target cluster for 7–10 days, is to search for exoplanet transit events in young open clusters—hence finding possibly the youngest exoplanets—the continuous and high-cadence observations produce data sets also valuable for young stellar variability study much relevant to planet formation (Bouvier et al. 2003). Here we present the light curve of GM Cep from 2009 to 2011 that reveals T Tauri-type flares and UXor-type variability, with the possible detection of cyclic occultation events by a dust clump in the circumstellar disk.

2. Light Curves and Color Variations

All the CCD images were processed by the standard procedure of bias, dark and flatfield correction. The photometry of GM Cep was calibrated by a linear regression with the seven comparison stars listed by Xiao, Kroll, & Henden (2010). Images taken under inferior sky conditions were excluded in the analysis. Figure 1 shows the light curves of GM Cep and one of the comparison stars observed from mid-2009 to mid-2011. The variability of GM Cep is obvious. The star experienced a sharp brightening soon after our observations started in mid-2009, prompting us to follow this star closely beyond the YETI campaigns. Our intense monitoring started in 2010. A brightness dip, with a depth of $\Delta R \sim 0.82$ mag, lasting for 39 days, occurred, followed by gradual brightening (by ~ 1 mag) and fading. The falling and rising parts of the dip are roughly symmetric. In 2011, a dip also happened, but with rapid fluctuations. The star fluctuated some $\Delta R \sim 1.7$ mag in 2010 and also in 2009. We conclude that the sharp brightening in 2009 corresponded to the rising part of the dip seen in 2010. If so, the recurrent time scale of the dip would be 346 days, and the minimum of the dip brightened from 2009 ($R \sim 14.2$ mag), 2010 ($R \sim 13.9$ mag), to 2011 ($R \sim 13.2$ mag). When this trend is taken out, the gradual brightening and fading is more or less symmetric in time with the peak luminosity happening between two consecutive dips, much like the round-topped light curves seen in contact binaries. Such repeated dips plus a slow brightening and fading can be seen in the long-term light curve reported by Xiao, Kroll, & Henden (2010), who claimed no periodicity in the data perhaps because of the sparse sampling of the data.

Figure 2 shows the light curves of GM Cep in B, V, R bands since late 2006, with additional data taken from Sicilia-Aguilar et al. (2008) and AAVSO. Analysis by the NStED (NASA/IPAC/NExScI Star and Exoplanet Database) Periodogram Service, based on the Lomb-Scargle algorithm, shows the first-ranked peroid to be 311 d with a broad peak in the power spectrum, suggesting a quasi-periodicity, as shown in Figure 3. Such a recurrence time scale of 310–320 d indeed seems to coincide with the minima in the light curve (see Figure 2) at least for the last 5 cycles for which sampling has been sufficiently dense (Hu et al. 2012). In addition, superimposed on the above light variations, there are sporadic flaringlike episodes with amplitude less than 0.5 mag, each lasting for about 10 d, characteristic of T Tauri activity.

While the YETI campaigns are carried out in the R band, our intensified observations of GM Cep since 2010 included also those taken in the V band. The color changes during the dip, as well as during the brightening and fading episodes, are particularly revealing. Fig. 4 shows the R-band light curve and $V-R$ color variations in 2010/2011. The dip in the beginning has a depth of about $\Delta V \sim 0.68$ mag; so while the star became fainter (depth in R was 0.82 mag), the $V-R$ value decreased, i.e., its color turned bluer. During the general brightening, the star also became bluer.

To summarize, the light curve of GM Cep is characterized by (1) a brightness dip of about 1 mag lasting for a month, with a recurrence time scale of about a year, (2) in between the dips, a gradual brightening of about 1 mag, followed by a roughly symmetric fading, and superimposed on the above two, (3) intermittent flares $\lesssim 0.5$ mag, each lasting for several days.

3. Discussion

The abrupt behavior in GM Cep's light curve is not uncommon among Herbig Ae/Be stars, with modulations of various time scales, i.e., "cyclic but not exactly periodic" (Herbst & Shevchenko 1999), superimposed on deep minima. A flare with a blue color can be accounted for by enhanced accretion of clumpy material. Semkov & Peneva (2011) published the B, V, R, I light curves of GM Cep covering from mid-2008, i.e., one year earlier, but in lower cadence, than our data. Their data showed $R \sim 12$ mag in 2008 with no obvious dips, an obscuration event in 2009, and another one in 2010. These authors proposed that GM Cep is a UXor variable. At the end of their observations, in early 2011, the star reached again $R \sim 12$ mag, shown also in our data.

The most striking feature of the light curve of GM Cep is the month-long dips. There are various possible mechanisms to produce such a phenomenon, e.g., by star spots or a rotating accretion column, which has a typical time scale of a few hours to days. A notable case, the T Tauri star AA Tau, is known to show deep fading ($\sim$ 1.4 mag) lasting for about a week, believed to be caused by occultation by a warp in the magnetospheric accretion disk (Bouvier et al. 1999), with a quasi-cyclic time scale of 8.2 d (Bouvier et al. 2003, 2007). The dip phenomenon appears to be common among young stars with inner dusty disks (Herbst & Shevchenko 1999). In a study by CoRot satellite of the young star cluster NGC 2264, Alencar et al. (2010) found a fraction of 30–40% young stars exihibiting

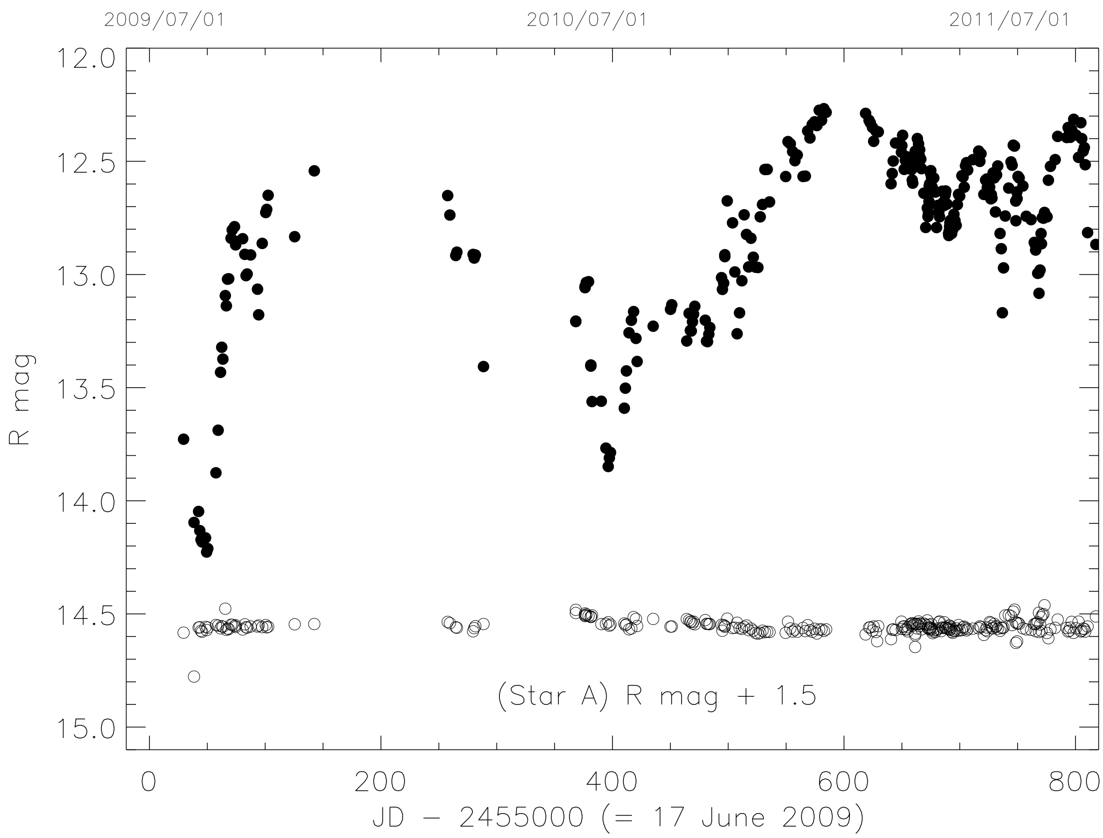

Fig. 1.— The R-band light curves of GM Cep (top) and of a comparison star (bottom, offset by 1.5 mag for display clarity) from mid-2009 to mid-2011. Typical photometric errors (0.005 mag) are smaller than the sizes of the symbols and are not shown.

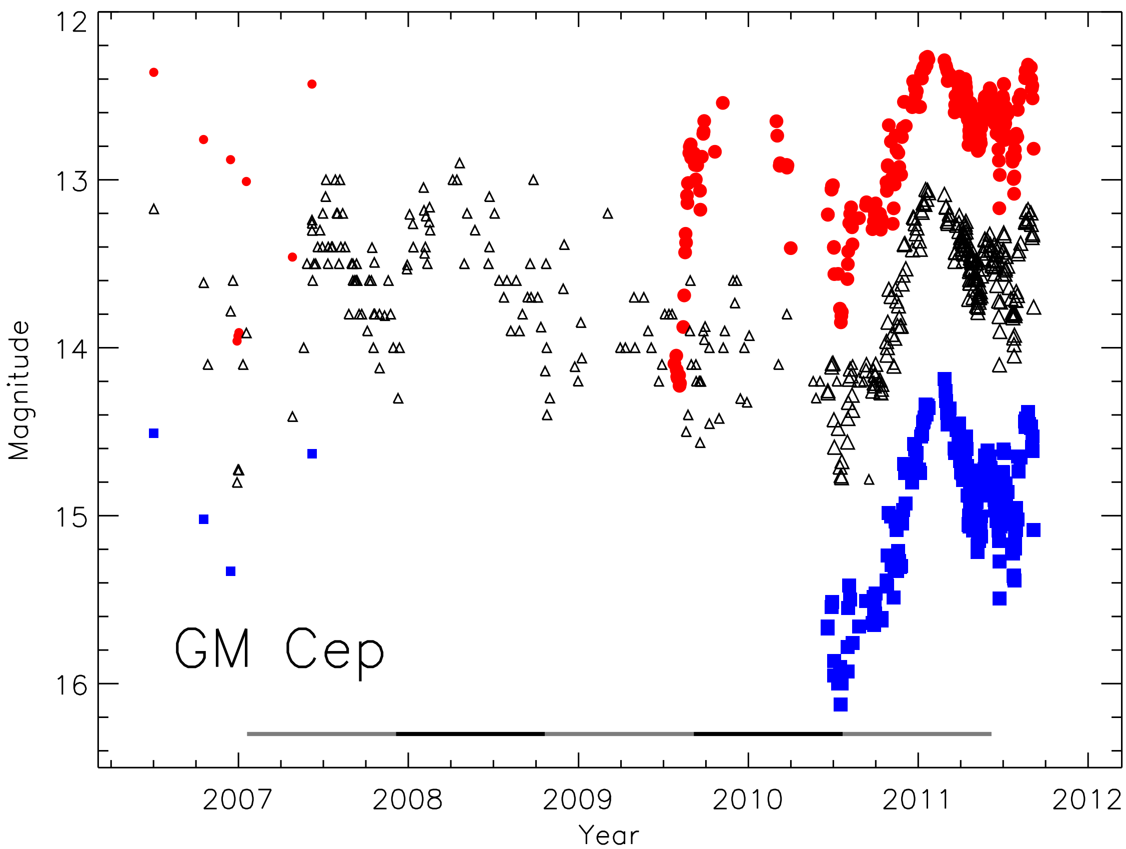

Fig. 2.— Light curves of GM Cep in B (denoted by red circles), V (black triangles), and R (blue squares) bands between late 2006 to 2011. Symbols with larger sizes, i.e., those after 2009, represent our observations. Each segment of the horizontal black and gray line is shown for duration of 320 days, to coincide roughly with the brightness dips.

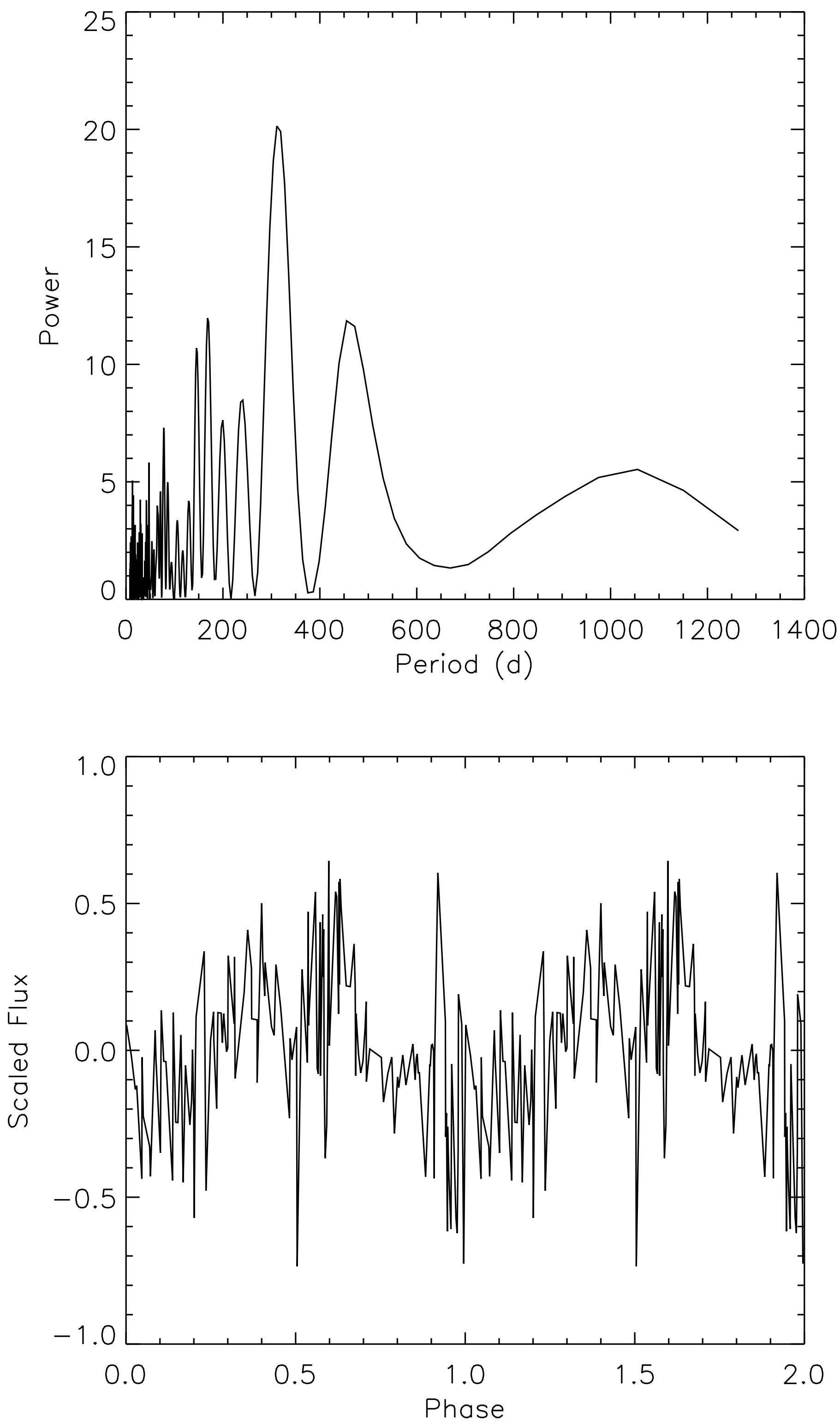

Fig. 3.— (*Top*) Power spectrum of the light curve in Figure 2 analyzed by the Lomb-Scargle algorithm, peaking at the period of 311 d. (*Bottom*) Phased light curve with the 311 d period.

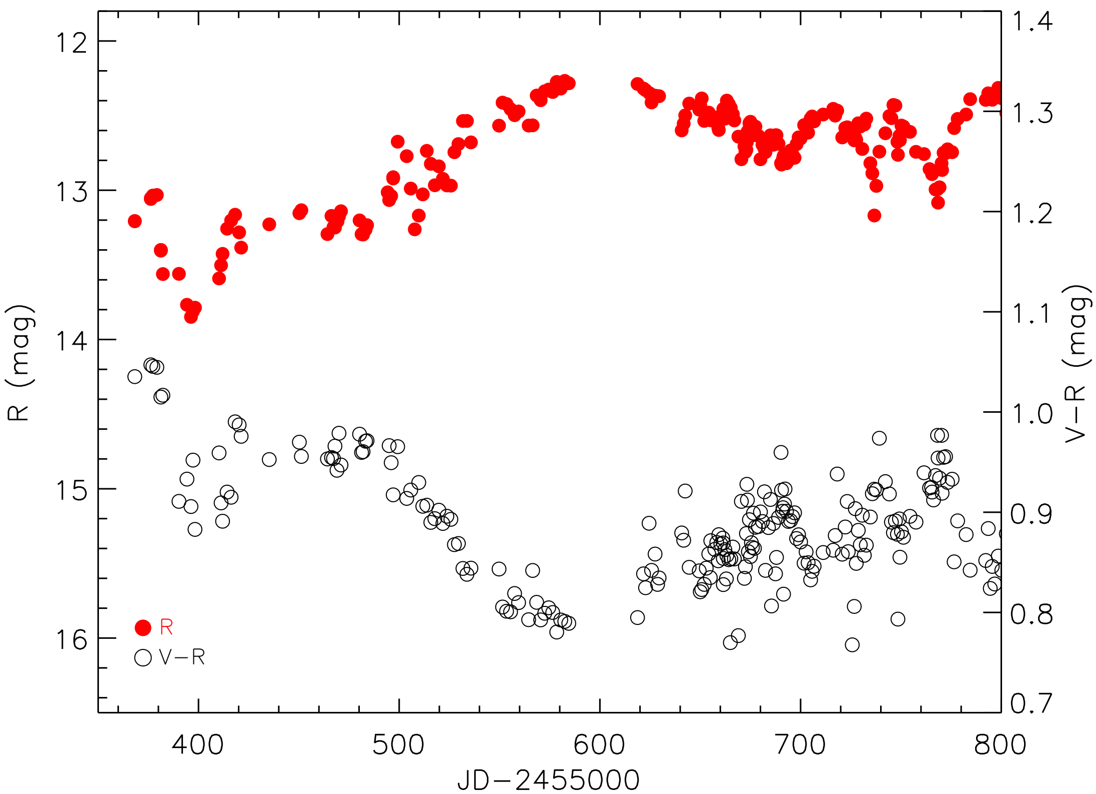

Fig. 4.— The R-band light curve (left y-axis) and the $V-R$ color variations (right y-axis, redder to the top) of GM Cep from mid-2010 to mid-2011. Note the star became blue when faintest and brightest.

obscuration variations.

We propose that the month-long dip seen in GM Cep is a manifestation of obscuration by an orbiting dust concentration in the circumstellar disk, i.e., GM Cep is a UXor-type variable, as reported by Xiao, Kroll, & Henden (2010) and by Semkov & Peneva (2011). If so, the orbital period of the dip gives information on the distance of the clump from the star, whereas the duration of the obscuration and amount of starlight extinction, give, respectively, the size and the column density of the clump. The mass of the star is uncertain for this PMS star, but assuming 2.1 $M_\odot$ (Sicilia-Aguilar et al. 2008), a Keplerian motion, and a period of P=320 days, the orbital distance of the clump would be $r \sim 1.2$ AU. The duration of the obscuration $t \sim 39$ days is related to the half-size of the clump R_c by $t/P = (2R_c)/(2\pi r)$; hence $R_c \sim 0.4$ AU, or about 15–30 stellar radii (Sicilia-Aguilar et al. 2008).

The extinction A_λ at wavelength λ is related to the amount of obscuring dust along the line of sight, i.e., $A_\lambda = 1.086\, N_d\, \sigma_d\, Q_{ext}$, where N_d is the column density of the dust grains, σ_d is the geometric cross section of a grain of a radius of a $\sigma_d = \pi a^2$, and Q_{ext} is the dimensionless extinction efficiency factor. Stars as young as GM Cep should have large grains settled into the midplane, but because the disk is inclined (Sicilia-Aguilar et al. 2008), we assume that the obscuration is caused mostly by small dust grains with an average radius of $a \sim 0.1$ μm, thus $Q_{ext} \sim 1$, cautiously noting the possibility of abnormal dust sizes in the disk (Sicilia-Aguilar et al. 2008). It follows from the observed obscuration of 0.68 mag in the V band that $N_d = 2.0 \times 10^9\,\mathrm{cm}^{-2}$. This amount of intervening dust is hardly excessive. The flux drop during the dip phase, ~ 1 mag, is comparable to the extinction of the star $A_V \sim 1.5$ (Contreras et al. 2002; Sicilia-Aguilar et al. 2004), a value commonly seen among CTTSs. The moderate extinction also indicates a line of sight out of the disk plane. What is intriguing in GM Cep of course is the distinct on-off behavior of the obscuration. The column mass density is, given the same amount of extinction, proportional to the dust size a, and in this case is $\Sigma \sim 2.9 \times 10^{-5}$ g cm^{-2}. Even for $a = 10$ μm grains, the column mass density would be still several orders less than the minimum solar nebula, for which Σ is a few thousands g cm^{-2} at 1 AU (Weidenschilling 1977)).

It is not clear whether the clump has a line-of-sight (radial) dimension comparable to its transverse size ($2R_c$) or is merely a ringlet. Even if it is spherical, thus yielding the maximum mass, the mean volume density would be $n_d = N_d/2R_c = 1.7 \times 10^{-4}\,\mathrm{cm}^{-3}$ at the clump's center. Given the proximity of the clump to the star (r = 1.2 AU), we assume the dust composition to be mostly silicates, having an average density of $\rho = 3.5$ g cm^{-3}. This leads to an estimated mass of $M_d = 2.3 \times 10^{21}$ g for the clump, about that of an asteroid, if the mass is uniformly spread. For a clump this substantial in size, our line of sight does not need to line up to the orbital plane in order to detect the occultation. From the fast rotation, the infrared spectral energy distribution, and the Hα profile, an intermediate inclination angle was inferred (Sicilia-Aguilar et al. 2008). A clump extending in radial direction would have been tidally unstable. The clump is thus extended along the orbit, but short radially.

The blueing phenomenon during the obscuration is most puzzling. It has been seen in UX Ori itself (Herbst & Shevchenko 1999) and other UXors (Grinin et al. 2001). Semkov & Peneva (2011) reported also the "color reversal" or the blueing effect in GM Cep, and attributed it to possible anomalous dust properties, or disk geometry such as self-shadowing or a piled up wall in the inner disk (Dullemond et al. 2003). One appealing proposal by Grinin et al. (1994) is that blueing happens when dust along the line of sight completely dims the star, and dust particles near the line of sight scatter preferentially blue light into the view, a mechanism supported by increased polarization during maximum extinction. In GM Cep when the clump blocks out the star, either the hot boundary layer — a region between the star and the active accretion disk — or the magnetospheric accetion column, must have contributed much to the emission during the dip phase.

It is interesting to note that, except for the flare events, the light curve of GM Cep, namely repeated occultation modulated by gradual, symmetric brightening and fading, bears resemblance to that of an eclipsing binary or an exoplanet transit with phase variations (Borucki et al. 2009), though the time and flux change scales are vastly different. In GM Cep the flares are caused by enhanced accretion activity, and the dip, as we propose here, by occultation of the central star by a patch of dust in the circumstellar disk. The gradual brightening and fading, then, is the result of the orbital modulation of reflected starlight, as witnessed in high-precision light curves of eclipsing binaries or transiting exoplanets (Borucki et al. 2009). Without the shape information of the clump, it is difficult to quantify this effect. But the amount of reflected light allows us to estimate the height of the clump. If the yearly brightening trend in 2009–2011 is removed, the gradual brightening in 2010 amounted to ~ 0.7 mag, meaning approximately an equal contribution between the reflected light and the direct starlight. Without knowledge on the density distribution and optical properties of dust, we made a simple analogy of dust grains as a translucent mirror, made up of a total number of $N_{\rm tot}$ particles. Assuming the Bond albedo a_B, the reflected light is $(L_*/4\pi r^2)\, \pi a^2 a_B N_{\rm tot}$, and an ensemble of dust on the back side of, and 1.2 AU away from, the star would yield $N_{\rm tot} \sim 3 \times 10^{36}/a_B$. A rudimentary estimate, assuming an albedo of 4% (cometary nuclei) thus gives a height not much less than the perimetrical dimension.

If our hypothesis holds, that the same clump has been responsible for the yearly dip, the clump must be dynamically stable. The mass we derived is only for the dust, and there is no evidence, even with a sufficient amount of associated gas, that the clump is on the verge of gravitational instability (Chang & Oishi 2010). In any case, the density of the clump is not likely to have a high contrast relative to the rest of the disk. In other words, it may be just a density inhomogeneity, such as a local dust concentration in a warped, spiral-armed disk or density enhancement by a companion star (Grinin et al. 1998), that gives rise to the characteristic light curve seen in GM Cep.

In conclusion, our photometric monitoring of GM Cep confirms its UXor nature. Moreover, the light curves and color variations suggest density inhomogeneity of dust in the young stellar disk. Such enhanced density contrast may be a signpost of the transition phase from grain growth to the onset of planetesimal formation. GM Cep may not be an isolated example, and intense monitoring should be carried out for young stars known to exhibit abrupt light variations. Further characterization of the clumpy disk of GM Cep, e.g., by polarization, infrared spectroscopy, and high angular resolution submillimeter imaging, at epochs in and out of the occultation, should shed light on our hypothesis of this interesting young star.

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