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Letter to the Editor

Effects of dust on light-curves of ϵ Aurigae-type stars

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ABSTRACT

Context. ϵ Auriga is one of the most mysterious objects in the sky. Previous modeling of its light-curve assumed a dark, inclined, non-transparent or semi-transparent dusty disk with a central hole. The hole was necessary to explain the light-curve with a sharp mid-eclipse brightening.

Aims. The aim of the present paper is to study the effects of dust on the light-curves of eclipsing binary stars and to develop an alternative physical model for ϵ Aur-type objects that is based on the optical properties of dust grains.

Methods. The code Shellspec was modified to calculate the light-curves and spectra of these objects. The code solves the radiative transfer along the line of sight in interacting binaries. Dust and angle-dependent Mie scattering were included in the code for this purpose.

Results. Our model of ϵ Aur consists of two geometrically thick flared disks: an internal optically thick disk and an external optically thin disk, which absorbs and scatters radiation. Disks are in the orbital plane and are almost edge-on. We argue that there is no need for a highly inclined disk with a hole to explain the current eclipse of ϵ Aur even if there is a possible shallow mid-eclipse brightening. We demonstrate that phase-dependent light scattering and the optical properties of the dust can have a significant effect on the light-curves of these stars and can even produce a mid-eclipse brightening. This is a natural consequence of the strong forward scattering. We also demonstrate that shallow mid-eclipse brightening might result from eclipses by nearly edge-on flared (dusty or gaseous) disks.

Key words. accretion, accretion disks – scattering – binaries: eclipsing – circumstellar matter – stars: individual: ϵ Aur

1. Introduction

ϵ Aur has eluded astronomers for a long time. This star is a bright object visible by the naked eye and has been known to be variable since almost two hundred years. It is an eclipsing binary with the longest known orbital period, 27.1 yr. A very rare eclipse that lasted for two years is almost over. However, the object, its origin and, in particular, the secondary component of this binary star remain mysterious. The extremely long orbital period and eclipse implies that the two objects are huge.

The primary, which is the main source of light, may be a relatively young, massive F0Ia super-giant with the mass of about 16 $M_\odot$ (Stencel et al. 2008) and radius of about 135 $R_\odot$ (Hoard et al. 2010). The secondary is not visible. Kuiper et al. (1937) suggested that it is a huge (>3000 $R_\odot$) partially transparent star. Nowadays, we believe that the secondary is a dark and mysterious object with a radius of about 9 AU and a mass of 13 $M_\odot$. Huang (1965) proposed that the secondary is a dark disk seen edge-on. Wilson (1971) and Carroll et al. (1991) argued that the observed sharp mid-eclipse brightening (MEB)[1] can only be explained by a tilted disk with a central opening. Ferluga (1990) suggested that the disk is a system of rings. The main weakness of this model is that it cannot explain what is inside the disk and why we do not see it. Stars with a sufficient mass to fit this model are too bright and black holes are ruled out because of the lack of X-rays. An alternative is that the primary is an old evolved post-AGB star with a mass of about 2.2 $M_\odot$ and that the secondary hides a main sequence B5 star with mass of about 5.9 $M_\odot$ in the center (Hoard et al. 2010; Kloppenborg et al. 2010; Takeuti 1986, and references therein).

There has been a wealth of studies during the current eclipse at various wavelengths. Orbital solutions were recently revisited by Stefanik et al. (2010) and Chadima et al. (2010). Kloppenborg et al. (2010, 2011) confirmed the dark disk with interferometric observations but they did not confirm the hole in the disk. The spectral energy distribution was studied by Hoard et al. (2010). These authors favor the post AGB+B5V model and conclude that the dust grains in the disk are unusually large (see also Lissauer et al. 1996). Wolk et al. (2010) analyzed X-ray observations. Recently, Chadima et al. (2010, 2011b) questioned the presence of sharp mid-eclipse brightening and suggested that the photometric variability seen during eclipse is intrinsic to the F-star.

The section below presents a motivation for this study and an outline of important physical and geometrical effects. These effects, dust and Mie scattering, were incorporated into the code Shellspec. It solves radiative transfer along the line of sight in 3D moving circumstellar environment (Budaj & Richards 2004; see also Budaj 2011; Miller et al. 2007; Tkachenko et al. 2010; Chadima et al. 2011a for some modifications and applications). In the next sections we apply this code to ϵ Aur.

2. Motivation

The standard explanation of the MEB relies on the presence of a disk and pure geometry. It requires a chain of strict assumptions. The disk is optically thick but geometrically thin. It has to be

[1] By a mid-eclipse brightening in ϵ Aur some authors understand only a relatively sharp local maximum that appeared in a few eclipses near the middle of the eclipse. We propose a slightly more general definition of the MEB or a new term (mid-eclipse excess). Our MEB or mid-eclipse excess is a convex feature near the middle of an eclipse bed. A common eclipse has a concave eclipse bed. In the pictures with reversed magnitudes it looks just the opposite.

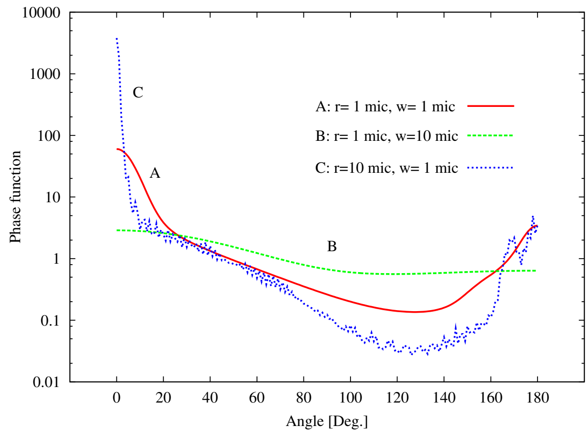

Fig. 1. Dust phase function as a function of angle for forsterite. Calculated for spherical particles with radii, r, equal to 1 and 10 micron for wavelengths, w, equal to 1 and 10 micron. Note the strong forward scattering peak near 0 degrees and less pronounced backward scattering peak near 180 degrees for larger grains at shorter wavelengths.

inclined with respect to the orbital plane, and must contain a central hole. The hole may not be present all the time, which requires a lot of energy to fill it in or to open it again because it resides in a region of a strong gravitational field. Moreover, this does not explain everything and raises the question why we do not see the object in the center.

There might be an alternative physical explanation of the MEB. It is natural that there is a smooth transition from the optically thick to optically thin disk until it eventually vanishes. The optical behavior of dusty medium can be described by the Mie theory and characterized by the microphysical properties of dust gains. These are the grain size or size distribution, complex refractive index or chemical composition, shape of grains, etc. The striking property of dust grains is that they do not scatter light isotropically but exhibit strong forward scattering, less pronounced backward scattering and weak side scatter. This dependence of scattered light on the angle between the dust grain, source of light, and the observer is referred to as a phase function. Figure 1 illustrates the behavior of the dust phase function of forsterite, which constitutes one of the most refractory, abundant, and opaque dust grains. Notice the strong forward scattering for angles close to zero. It is most pronounced for larger grains and at shorter wavelengths. Backward scattering for angles close to 180 degrees is not that pronounced but shows a similar behavior. These phase functions, scattering and absorption opacities were calculated using the Mie scattering code by Kocifaj (2004) and Kocifaj et al. (2008). The complex index of refraction of forsterite was taken from Jäger et al. (2003). To suppress the ripple structure that would appear in the phase function of spherical mono-disperse particles, the poly-disperse Deirmendjian (1964) distribution of particle sizes was assumed.

Let us assume a hypothetical "eclipsing binary star" that consists of a star (source of light) and a distant ball of optically thin dust. Both objects revolve around their center of mass. The dusty ball will scatter the light in the forward direction, creating a beam of light analogous to the light-house effect. Whenever the beam hits the observer, which happens mainly during the eclipse, a pulse will be detected. The dusty ball may also cause attenuation of the light from the source during the eclipse. These two effects will compete. If the main source of light disappears, e.g. during the total eclipse by some optically thick object, then scattering by the optically thin dust may completely dominate the observed radiation. Consequently, such a "naked" light-house effect might be a natural explanation of the MEB observed in some eclipsing binary stars.

Apart from the above mentioned effect we propose that the shallow MEB may also result from edge-on flared disks. Suppose that the disk is flared, homogeneous and optically thin (or at least partially transparent). Then the edges of the disk may have a larger effective cross-section and optical depth along the line of sight than the central part of the disk and consequently might attenuate the stellar light more effectively before and after the mid-eclipse. This effect relies mainly on the shape of the disk and opacity and is independent of the source of opacity, which is why it could work for both dusty and gaseous disks.

3. Observations

Observations that were used for comparison with our calculations were taken from the AAVSO database (Henden, priv. comm.). They were obtained by many observers who contributed to the database during the current eclipse of ϵ Aur. Only the observations in the V-filter were considered here. These observations indicate the presence of a shallow mid-eclipse brightening but it is not as sharp and pronounced as some might have anticipated. We fitted an eclipse bed (phases $\langle -0.19, 0.19\rangle$) with a quadratic function $y = a + bx + cx^2$ (see Fig. 3) and obtained the following coefficients: $a = 3.690 \pm 0.004$, $b = -1.1 \pm 0.2$, $c = 140 \pm 20$. The c coefficient is positive, which indicates that this part of the eclipse bed is a convex feature and thus represents a mid-eclipse brightening. Its error indicates that its significance is beyond 5σ. Notice that if $b \neq 0$ the maximum of the function is not in the middle of the eclipse. However, the quadratic term, which constitutes the MEB, still has the maximum at the center of the eclipse. This justifies a need for a more general definition of the MEB or a mid-eclipse excess. Presence of the linear term, longer ingress and steeper egress indicate that the disk is not perfectly symmetric, but suffers from some disturbance. Its leading part might be more extended or disk slightly inclined out of the orbital plane (warped?).

4. Light-curve of ϵ Aur

In this section we will carry out calculations of the light-curves and study effects outlined in Sect. 2. If not mentioned otherwise, we will follow the alternative model of ϵ Aur (Hoard et al. 2010) and assume that the main source of light is a star with radius of 135 $R_\odot$, $T_{\rm eff} = 7750$ K, and mass of 2.2 $M_\odot$. A quadratic limb darkening for filter V was applied to it with coefficients 0.38, 0.28 (Claret 2000). Its spectrum was approximated by a blackbody. The second object is separated by 18.1 AU, has a mass of 5.9 $M_\odot$, and is enshrouded in a disk. Light-curves were computed for 550 nm and a polydisperse distribution of particle sizes with a typical radius of 4 μm.

4.1. Effect of forward scattering on the eclipse

This section illustrates the pure effect of forward scattering on the light-curve of ϵ Aur during the *hypothetical total eclipse*. We assume that the main source of light is eclipsed by an opaque dark and geometrically thick disk seen edge-on. To observe a "pure" forward scattering effect, we assume that the eclipse is total, i.e., the star is completely hidden behind the optically and geometrically thick disk. Calculations are presented in Fig. 2. The opaque disk has the shape of a slab with radius of 730 $R_\odot$ and

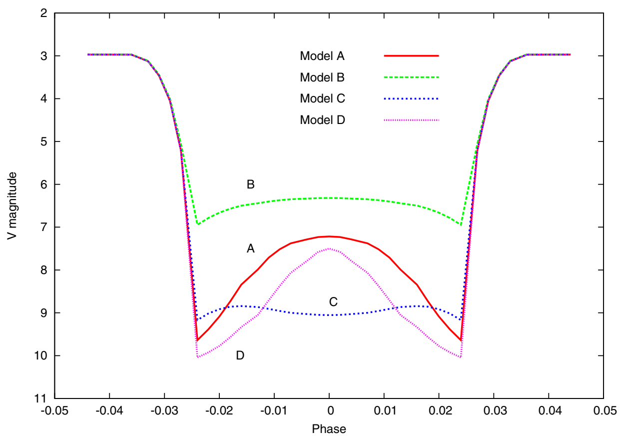

Fig. 2. Hypothetical total eclipse of ϵ Aur by a dark, geometrically and optically thick, edge-on disk of dust. This disk causes the total eclipse and does not transmit any light during the eclipse. Apart from this non-transparent disk our model includes optically thin dust regions of different shapes: model (A) has a spherical shell of dust, model (B) has a flat-disk region, model (C) has a flared disk, and model (D) has a sort of jet-like region. These regions scatter the light toward the observer, which is seen during the total eclipse. Because of the strong forward scattering this scattered light may be most intense in the middle of the eclipse and might give rise to a mid-eclipse brightening. See the text for more details.

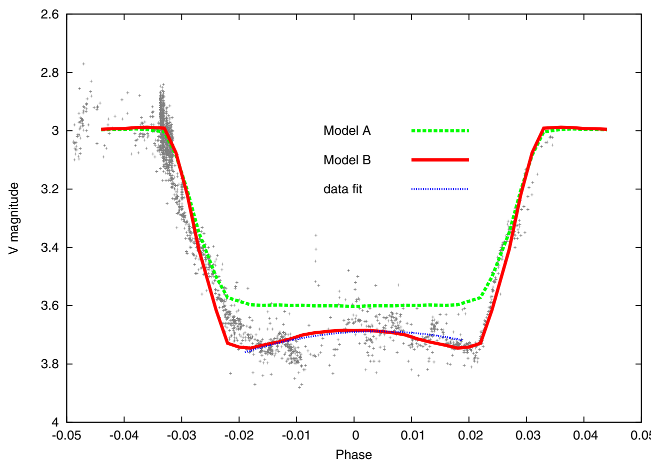

Fig. 3. Eclipse of ϵ Aur by a dark, geometrically thick, flared disk of dust. The disk consists of two parts: (1) the flared optically thick part that causes most of the eclipse, and (2) a flared optically thin part that causes additional absorption, scattering and mid-eclipse brightening. Model (A): disk has only one part (1). Model (B): disk has both parts part (1) and part (2). Mid-eclipse brightening arises mainly because the edges of the flared disk are more effective in the attenuation of the stellar light than the central parts of the disk. Thin dotted line is a best-fit quadratic function to the eclipse bed. Crosses - observations from AAVSO (Henden, priv. comm.).

thickness of 272 $R_\odot$. Apart from the opaque disk we included a few different optically thin dust components that scatter the light toward the observer: model (A) has a spherical shell of dust with a radius of 400 $R_\odot$ and density of 5×10^{-18} g cm^{-3}; model (B) has a slab of dust above and below the opaque disk (sort of atmosphere) that is 250 $R_\odot$ thick with density of 5×10^{-18} g cm^{-3}; model (C) is a flared disk. The flared disk in our model has the shape of a rotating wedge with an opening angle. In this case we assumed an opening angle of 50 degrees and density of 0.8×10^{-18} g cm^{-3}; model (D) has the shape of a bipolar outflow (or a jet perpendicular to the opaque disk) with half-opening angle of 30 degrees, extending from the center up to 400 $R_\odot$, and dust density of 2×10^{-17} g cm^{-3}. One can indeed observe the above mentioned MEB in most cases. Interestingly, a flared disk may scatter more light before and after the mid-eclipse. Jets or structures with central dust concentrations may provide a quite sharp MEB similar to that claimed in a few past eclipses of ϵ Aur. In general, the shape of the light-curve or spectral lines would be given by the shapes of the opaque and non-opaque objects, the geometry of the eclipse, wavelength, properties of the dust and gas such as its density, temperature, chemical composition, velocity field, and grain size. In this configuration the amount of scattered light can reach a few percent but it heavily depends on the parameters mentioned above, particularly on those that determine the width of the forward scattering peak and angle between the scattering object, source of light, and observer.

4.2. Effect of a flared edge-on disk on the eclipse

The previous section demonstrated the effect of a pure forward scattering during the *hypothetical total eclipse of ϵ Aur*. However, in reality, the disk may not be thick enough to cause the total eclipse and the eclipse will be only partial. Our first experiments with disks of various shapes revealed that if the eclipse is partial and the disk has the shape of a slab, it is very difficult to reproduce the observed shallow MEB. In Sect. 2 we suggested another way that optically thin but geometrically thick flared disks might also produce a shallow MEB. That is why in this section we study partial eclipses by flared disks. The best fit to the observations (not necessarily the only possible solution) had the following geometry and components: (1) an optically and geometrically thick flared disk with an opening angle of about 7.5 degrees and radius of 690 $R_\odot$ (3.2 AU), immersed in (2) an optically thin and geometrically thick flared disk with an angle of 28 degrees and radius of 690 $R_\odot$ and density of 6×10^{-18} g cm^{-3}. Both disks were located in the orbital plane and were almost edge-on with the inclination of the orbital plane of 89.1 degrees. Synthetic light-curves are compared to the observations (V band) in Fig. 3. The dust phase function was convolved with the normalized limb-darkened profile with the full width corresponding to the angular diameter of the F-star as seen from the center of the disk. In this way we also took into account the finite dimension of the source of light in the calculations of the scattering.

We demonstrated the effect of forward scattering and a flared disk on the eclipse of ϵ Aur. However, there are other objects in which this mechanism may be important. Pre-main sequence stars often contain dusty accretion disks. Evolved objects, symbiotic Miras and/or AGB stars may also contain dusty regions of various shapes where phase-dependent Mie scattering might play an important role. Vinković et al. (2004) studied bipolar outflow structures in the dusty winds of AGB stars by 2D radiative transfer with isotropic scattering. Kotnik-Karuza et al. (2007) studied the properties of the circumstellar dust during obscuration events in the symbiotic Miras. Kudzej (2006) mentioned seventeen other eclipsing binary systems with mid-eclipse brightening and suggested that it is caused by the refraction in the atmospheres of stars.

5. Conclusions

A new alternative model of the ϵ Aur type stars was suggested. This model is based on the optical properties of dust grains. It assumes that dust concentrates in two regions: an optically thick disk and optically thin regions of different shapes. We demonstrated that an optically thick flared disk coated with an optically thin layer can reproduce the current eclipse observations of ϵ Aur very well. The model takes into account Mie scattering on dust, i.e., extinction caused by absorption and scattering as well as thermal and scattering emission.

We demonstrated that angle-dependent Mie scattering is important in these systems. Under certain circumstances, mainly if the dark dust is eclipsing a strong source of light, the forward scattering on dust can be crucial and can even produce a mid-eclipse brightening. We also demonstrated that near edge-on flared disks can produce eclipses with a shallow mid-eclipse brightening and that this might be an explanation of the shallow mid-eclipse brightening feature of ϵ Aur.

This model provides an alternative to an inclined disk with a central hole invoked to explain systems with mid-eclipse brightening. It does not raise the question why we do not see the object in the center of the disk. We may not see it because in our model it may be obscured by the disk. Potential variability in the mid-eclipse brightening might be caused by subtle changes in the remote, low density, optically thin regions of dust located at low gravitational potential, or by small changes in the inclination (or warping) of the disk and does not have to involve dense matter at high gravitational potential in the central hole of the disk.

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