A NEW APPROACH FOR PROBING CIRCUMBINARY DISKS

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ABSTRACT

Circumbinary disks are considered to exist in a wide variety of astrophysical objects, e.g., young binary stars, protoplanetary systems, and massive binary black hole systems in active galactic nuclei (AGNs). However, there is no definite evidence for the circumbinary disk except for some in a few young binary star systems. In this Letter, we study possible oscillation modes in circumbinary disks around eccentric and circular binaries. We find that prograde, nonaxisymmetric waves are induced in the inner part of the circumbinary disk by the tidal potential of the binary. Such waves would cause variabilities in emission line profiles from circumbinary disks. Because of prograde precession of the waves, the distance between each component of the binary and the inner edge of the circumbinary disk varies with the beat period between the precession period of the wave and the binary orbital period. As a result, light curves from the circumbinary disks are also expected to vary with the same period. The current study thus provides a new method to detect circumbinary disks in various astrophysical systems.

Key words: accretion, accretion disks – binaries: general – black hole physics – galaxies: nuclei – planetary systems: protoplanetary disks – stars: formation

1. INTRODUCTION

Astrophysical disks are ubiquitous in the various systems of the universe: star–compact object systems, star–planet systems, active galactic nuclei (AGNs), and so forth. These disks surround the individual objects as a circumobject disk. If the object surrounded by a rotating disk is a binary, the disk is called a circumbinary disk (see Figure 1 for a schematic view of the circumbinary disk).

About 60% of main-sequence stars are considered to be born as binary or multiple systems (Duquennoy & Mayor 1991). Numerical simulations have confirmed that young binary stars embedded in dense molecular gas have a circumstellar disk (Artyukhov & Lubow 1996a; Bate & Bonnell 1997; Günther & Kley 2002, 2004) and that a circumstellar disk is also formed around each star (Bate & Bonnell 1997; Günther & Kley 2002, 2004). Indeed, direct imaging of the circumstellar disk was successfully achieved by interferometric observations of a few young binary systems including GG Tau (Dutrey et al. 1994) and UY Aur (Duvert et al. 1998).

In the early stage of planet formation, a planet orbiting a star will be embedded in a rotating disk (hereafter, circumstellar disk) surrounding them. Kley & Dirksen (2006) showed, by performing numerical simulations, that the circumstellar disk becomes eccentric due to the resonant interaction between the planet and the disk. Such a planet–disk interaction also causes the significant evolution of the orbital elements of the planet, which gives a possible explanation about the observed high orbital eccentricities in extrasolar planetary systems (Goldreich & Sari 2003). The direct probing of the circumstellar disk is, therefore, a key to testing this scenario.

Massive black holes are considered to co-evolve with their host galaxies (Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000). There is inevitably an evolutionary stage as a binary black hole in the course of galaxy merger until the coalescence of two black holes (Begelman et al. 1980; Mayer et al. 2007; Hayasaki 2008). Hayasaki et al. (2007) found that if a binary black hole is surrounded by a circumbinary disk, mass is transferred from the disk to each black hole. The system then has a triple disk composed of an accretion disk around each black hole and a circumbinary disk as a mass reservoir around the binary (Hayasaki et al. 2008). There is, however, still little evidence for the circumbinary disk as well as for the binary black hole itself. Therefore, the detection of the circumbinary disk is also one of the important scientific motivations in probing massive binary black holes with parsec/subparsec separations. Quite recently, Bogdanović et al. (2008) and Dotti et al. (2008) proposed the hypothesis that SDSSJ092712.65+294344.0 is a massive binary black hole by interpreting the observed emission line features as those arising from the mass-transfer stream from the circumbinary disk.

There are many phenomena caused by oscillations in circumstellar/accretion disks. One of the most famous among them is superhumps. A superhump is a periodic luminosity hump on the light curves in an accreting binary system, with a slightly longer period than the orbital period of the binary. The superhump phenomenon was first discovered in the SU Ursae Majoris class of dwarf novae, which consists of a white dwarf and a late-type star with a low mass ratio, less than 0.2 (Patterson 1979; Vogt 1980). It is attributed to the precession of a deformed accretion disk induced by the tidal potential of the binary (Osaki 1985). Lubow (1991) showed that the deformation of the disk is due to the growth of an eccentric (i.e., $m = 1$) perturbation through nonlinear coupling with the tidal potential. Hitherto, no phenomena caused by oscillation modes have been detected in circumbinary disks.

In this Letter, we investigate the tidally induced oscillation modes in circumbinary disks. These modes can be driven by resonantly excited modes at particular resonance radii, which are similar to the ones responsible for superhumps in dwarf novae systems. The Letter is organized as follows. In Section 2, we derive the azimuthally and temporally averaged tidal potential around an eccentric binary and discuss the possible oscillation modes and their frequencies in circumbinary disks. Section 3 is devoted to a summary and discussion.
2. TIDALLY INDUCED SPIRAL WAVES

We consider two gravitationally bound point masses surrounded by a circumbinary disk. The point masses follow Kepler’s third law, while the geometrically thin circumbinary disk has a rotation slightly deviated from Keplerian rotation because of the tidal potential of the binary. We assume that the circumbinary disk is truncated at an inner radius, \( r_{\text{in}} \), by the resonant interaction with the binary (e.g., Artymowicz & Lubow 1994), but extends outward to a large distance.

2.1. Tidal Potential

First, we consider the tidal potential around an eccentric binary. In the inertial frame of reference centered on the common center of the binary, the gravitational potential can be written as

\[
\Phi(r, \theta, t) = \frac{GM_1}{|r - r_1|} - \frac{GM_2}{|r - r_2|} = \frac{GM_1}{\sqrt{r^2 - 2rr_1\cos(\theta - \phi) + r_1^2}} - \frac{GM_2}{\sqrt{r^2 - 2rr_2\cos(\theta - \phi + \pi) + r_2^2}},
\]

(1)

where \( M_1 \) and \( M_2 \) are the masses of the primary and secondary components, respectively, \( r_1 \) and \( r_2 \) are their position vectors, and \( \phi \) is the true anomaly of the primary component. Here, \( r_i (i = 1, 2) \) periodically varies with time because of the orbital eccentricity and is given by

\[
\frac{r_i}{a} = \frac{\eta_i(1 - e^2)}{1 + e \cos f},
\]

(2)

where \( a \) is the semimajor axis, and \( \eta_1 \) and \( \eta_2 \) are \( q/(1 + q) \) and \( 1/(1 + q) \) with mass ratio \( q = M_2/M_1 \), respectively.

Azimuthally and temporally averaging Equation (1) with an assumption of \( r \gg r_1 \) and \( r \gg r_2 \), we obtain the averaged binary potential over one orbital period, \( \bar{\Phi}(r) \), in the form

\[
\bar{\Phi}(r) = 4\pi \int_0^{2\pi} \int_0^{2\pi} \Phi(r, \theta, t) \, d\theta \, d\Omega_{\text{orb}} = \frac{GM}{r} \left[ 1 + \frac{3}{2} \frac{q}{(1 + q)^2} \right],
\]

(3)

where \( M \) is the binary mass \( M_1 + M_2 \). Here, we have neglected terms of the order of \( e^5 \) or higher and made use of the following expansion formula:

\[
\frac{r_i}{a} = \eta_i \left[ 1 - e \cos \Omega_{\text{orb}} + \frac{e^2}{2} (1 - \cos 2\Omega_{\text{orb}}) + O(e^3) \right]
\]

(e.g., Murray & Dermott 1999, ch. 4, p 160). Note that these series converge for \( e \lesssim 0.66 \).

The second term on the right-hand side of Equation (3) gives the tidal perturbation potential around the eccentric binary:

\[
\Phi_{\text{tid}}(r) = -\frac{GM}{4r} \left( \frac{a}{r} \right)^2 \frac{q}{(1 + q)^2} \left( 1 + \frac{3}{2} e^2 \right).
\]

(4)

From this equation, Equation (3) is rewritten as \( \bar{\Phi}(r) = -GM/r + \Phi_{\text{tid}}(r) \). It is noted from Equation (4) that the tidal force acts more strongly on the circumbinary disk around an eccentric binary than around a circular binary.

2.2. Trapped Waves

Let us now consider oscillations in the form of the normal mode which varies as \( \exp[i(\omega t - k \cdot r - m \phi)] \), with \( \omega \) being the oscillation frequency, and \( k \) and \( m \) being the radial and azimuthal wave numbers, respectively. Then, the local dispersion relation for these oscillations is given by

\[
(\omega - m\Omega)^2 - k^2 = k_c^2 c_s^2,
\]

(5)

where \( c_s \) is the sound speed, \( \Omega \) is the rotation frequency of the circumbinary disk, and \( k \) is the epicyclic frequency given by

\[
\kappa = 2\Omega(2\Omega + r d\Omega/dr).
\]

(6)

From Equation (5), the region where a wave can propagate, i.e., \( k_c^2 > 0 \), is given by

\[
\frac{\omega}{m} < \Omega - \frac{k}{m} \quad \text{or} \quad \frac{\omega}{m} > \Omega + \frac{k}{m}.
\]

(7)

In other words, waves can propagate inside the inner Lindblad resonance (ILR) radius, where \( \omega/m = \Omega - \kappa/m \), or outside the outer Lindblad resonance (OLR) radius, where \( \omega/m = \Omega + \kappa/m \). However, we are interested only in the former type of waves with \( 0 < \omega/m < \Omega - \kappa/m \), because they are trapped in the region between the inner radius of the circumbinary disk and the ILR radius, and are thus possibly excited. All other waves are running waves and will never be excited.

Kato (1983) pointed out that the only possible global waves in nearly Keplerian disks such as circumbinary disks are low-frequency, one-armed (i.e., \( m = 1 \)) waves. Waves with \( m \neq 1 \) have wavelengths much smaller than \( r \) and are expected to damp rapidly as a result. In the case of a circumbinary disk around a binary with nonextreme mass ratio, however, mass transfer occurs from two points of the inner edge of the circumbinary disk to each component of every binary orbit (Hayasaki et al. 2007). This might suggest that two-armed (i.e., \( m = 2 \)) spiral waves are excited in the circumbinary disk through coupling with the tidal potential.

2.3. Precession Frequency and Beat Frequency

From Equation (3), the orbital angular frequency of the circumbinary disk under the tidal perturbation potential is given by

\[
\Omega \simeq \Omega_{\kappa} \left[ 1 + \frac{3}{8} \left( \frac{a}{r} \right)^2 \frac{q}{(1 + q)^2} \left( 1 + \frac{3}{2} e^2 \right) \right],
\]

(8)

where \( \Omega_{\kappa} = \sqrt{GM/r^3} \) is the Keplerian angular frequency of the circumbinary disk. Substituting Equation (8) in Equation (6), we have

\[
\kappa \simeq \Omega_{\kappa} \left[ 1 - \frac{3}{8} \left( \frac{a}{r} \right)^2 \frac{q}{(1 + q)^2} \left( 1 + \frac{3}{2} e^2 \right) \right],
\]

(9)
In general, the eigenfrequency and the extent of the propagation region can be estimated, using the WKBJ approximation, by searching for $\omega$ that satisfies $\int k_r dr \sim n\pi$ with an integer $n$, where the integration is performed over the propagation region. Given that the pressure gradient restoring force is much smaller than the gravity in geometrically thin circumbinary disks and that the waves are trapped in the inner part of the disk, the precession frequency of an $m$-armed spiral wave, $\omega_{p,m}$, is approximately given by

$$\omega_{p,m} = m\Omega - \kappa$$  \hspace{1cm} (10)

at the inner disk radius, $r = r_{in}$. More rigorously, in the case of a one-armed ($m = 1$) wave, one can show that the precession frequency is significantly lower than, but is still of the order of, $\Omega(r_{in}) - \kappa(r_{in})$. Thus we write it as

$$\frac{\omega_{p,1}}{\Omega_{orb}} \lesssim \frac{3}{4} \left( \frac{a}{r_{in}} \right)^{7/2} \frac{q}{(1+q)^2} \left( 1 + \frac{3}{2}e^2 \right).$$  \hspace{1cm} (11)

Note that for $m = 1$ modes, the precession frequency is positive and much lower than the orbital frequency. This feature means that the $m = 1$ waves with wavelengths comparable to $r_{in}$ are trapped in the inner part of the circumbinary disk.

On the other hand, the precession frequency of an $m$-armed ($m \neq 1$) wave normalized by the orbital frequency of the binary is obtained as

$$\frac{\omega_{p,m}}{\Omega_{orb}} = \left( \frac{a}{r_{in}} \right)^{3/2} \left[ m - 1 \right.\
\left. + \frac{3}{8} (m + 1) \left( \frac{a}{r_{in}} \right)^2 \frac{q}{(1+q)^2} \left( 1 + \frac{3}{2}e^2 \right) \right]^{1/2}.\hspace{1cm} (12)$$

Thus, the precession frequency of $m \neq 1$ waves is approximately given by $(m - 1)\Omega_{orb}/r_{in}$. Note that these waves have wavelengths much shorter than those of $m = 1$ waves.

It is instructive to evaluate the beat periods for some important modes. The beat frequency for an $m$-armed spiral wave is defined by

$$\Omega_{beat,m} = \Omega_{orb} - \omega_{p,m}.$$  \hspace{1cm} (13)

From Equation (13), we obtain the beat period as

$$P_{beat,m} = P_{orb} \left( 1 - \frac{\omega_{p,m}}{\Omega_{orb}} \right)^{-1}.$$  \hspace{1cm} (14)

According to the tidal truncation theory (Artymowicz & Lubow 1994), the circumbinary disk around the binary with a low-moderate orbital eccentricity is truncated at $r_{in} \simeq 2.08a$. In an equal-mass binary ($q = 1$) with $e = 0.5$, the beat period of the $m = 1$ mode is $P_{beat,1} \simeq 1.03P_{orb}$, whereas that of the $m = 2$ mode is $P_{beat,2} \simeq 1.34P_{orb}$.

3. SUMMARY AND DISCUSSION

We have studied possible oscillation modes in a circumbinary disk induced by the tidal potential of a binary system such as young binary stars, protoplanetary systems, and massive binary black holes in AGNs. We have pointed out that observationally interesting waves are those with precession frequency $\omega_{p,m}/m \lesssim \Omega(r_{in}) - \kappa(r_{in})/m$, where $r_{in}$ is the inner radius of the circumbinary disk. These waves are trapped between the inner disk radius and the ILR radius, where the pattern speed of the wave is equal to $\Omega(r) - \kappa(r)/m$. Among them, only $m = 1$ waves have wavelengths comparable to the inner disk radius. When the $m = 1$ mode is dominant, the inner region of the circumbinary disk becomes eccentric and precesses very slowly (see, for example, Kley & Dirksen 2006; MacFadyen & Milosavljević 2008). On the other hand, waves with $m \neq 1$ have much shorter wavelengths and affect only the innermost narrow region of the disk. For example, if the $m = 2$ mode is dominant, the disk inner edge is deformed to an elliptical shape, which precesses at the local Keplerian frequency.

It is important to note that there are two types of excitation mechanism for these waves. In circular binaries, non-axisymmetric perturbations in the disk can grow through the resonant interaction with the tidal potential at particular resonance radii, a mechanism similar to that for superhumps in dwarf novae systems. For example, the growth of an eccentric perturbation is driven by the excitation of an $m = 2$ wave at the 1:3 OLR radius. In addition to this mechanism, in eccentric binaries, a one-armed ($m = 1$) spiral wave can also be excited through direct driving as a result of a one-armed ($m = 1$) potential (Artymowicz & Lubow 1996b).

Whatever the excitation mechanism, the deformed inner part of the circumbinary disk precesses at the frequency given by Equation (11) for the $m = 1$ mode and Equation (12) for the $m = 2$ mode. Since the velocity field in the disk is also perturbed by the waves, the emission line profiles from the inner part of the circumbinary disk will vary with the precession period. Such a variability has a distinct feature and will easily be observed. Since the $m = 1$ mode is a low-frequency, eccentric mode, the relative intensity of the violet (V) and red (R) peaks of double-peaked line profiles varies with a long period, e.g., $\sim 40P_{orb}$ for an equal-mass binary with $e = 0.5$. Such a line-profile variability caused by $m = 1$ waves has long been known as the V/R variation in Be stars, B-type stars with circumstellar decretion disks (e.g., Porter & Rivinius 2003). In contrast, if the $m = 2$ mode is dominant, the double-peaked profiles stay symmetric, but their peak separations (and FWHMs) will vary with a short period of $\sim 2.5P_{orb}$ irrespective of binary parameters.

In addition to these line-profile variabilities, another type of variability from circumbinary disks is expected. There is the beat between the orbital frequency of the binary and the precession frequency of the circumbinary disk. The beat period is slightly longer than the orbital period for $m = 1$ and $m = 2$ modes, as seen from Equations (11), (12), and (14). The radiation emitted from the circumbinary disk through the tidal dissipation is expected to vary periodically with the beat period, because the distance between each component of the binary and the inner edge of the circumbinary disk periodically changes. Moreover, the mass transfer rate from the circumbinary disk to each binary component is also expected to vary with the same period, because of angular momentum removal by the tidal torques. Therefore, the circumbinary disk perturbed by a trapped density wave will show the light-curve modulation at the beat period.

As for observability, the light-curve modulation caused by an $m = 1$ deformation is expected to be detected more easily than those caused by the $m \neq 1$ one. This is because the $m = 1$ wave
can exist globally in the circumbinary disk, while the $m \neq 1$ waves exist only in a narrow region.

In this Letter, we have shown that variabilities with the beat period and/or the precession period are expected as a natural consequence of the tidal interaction between a binary and a circumbinary disk and that one can identify circumbinary disks in terms of these periodic variabilities. This provides a new method to probe circumbinary disks in various astrophysical systems. In a forthcoming paper, we will perform a more detailed analysis of the mode characteristics, including numerical simulations.

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