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CIRCUMSTELLAR AND CIRCUMBINARY DISKS IN ECCENTRIC STELLAR BINARIES

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RESUMEN

Investigamos la existencia de trayectorias estables, donde el gas puede acumularse y formar discos de acreción, alrededor de estrellas que forman parte de sistemas binarios de órbitas excéntricas. Dado que el potencial depende del tiempo, no existen órbitas fijas, cerradas y periódicas. En su lugar, buscamos *lazos invariantes*: curvas cerradas cuya forma varía en sincronía con la fase orbital del sistema binario. Los lazos invariantes que no se auto-intersectan, pueden formar el armazón sobre el que se puede tener discos circunestelares y circumbinarios en estos sistemas. Estudiamos la extensión de las regiones en espacio fase donde estos lazos invariantes sin intersección existen y encontramos que ésta depende de la razón de masa de las estrellas y la excentricidad orbital, con una fuerte dependencia del segundo factor. El descubrimiento reciente de planetas en sistemas binarios de separación pequeña hace que el presente trabajo tenga una gran relevancia.

ABSTRACT

We study the existence of stable trajectories, where gas could accumulate to form accretion discs, around stars that form binary systems in eccentric orbits. Since the potential is time dependent, no fixed, periodic, close orbits exist. Instead, we search for *invariant loops*: closed curves that change shape in synchronism with the binary orbital phase. Non-intersecting loops can provide the scaffolding for circumstellar and circumbinary discs in these systems. We investigate the range of regions in phase space where these non-intersecting loops can exist and find this to depend on both, the mass ratio of the stars and their orbital eccentricity, with a strong dependence on the latter. The recent discovery of planets within close binary systems makes this work very relevant.

Key Words: planetary systems: protoplanetary disks — stars: binaries — stars: circumstellar matter — stellar dynamics

1. INTRODUCTION

There are two basic shapes in the Universe. The force of gravity, being isotropic, tends to produce spherical objects. But angular momentum conservation tends to produce disk-like objects when the system is dissipative. These two basic shapes are widespread across the Universe, and in some instances can be found together, as in ringed planets, or polar ring galaxies. Because of their simplicity, spherical theoretical models are usually the first to be tried, like the early spherical collapse models for protostars (Larson 1969). However, axisymmetric disk-like models are usually not far behind (Larson 1972). As early as 1796, Laplace was aware of the importance of disks in the formation of planetary systems, when he posited his *Nebular Hypothesis* for the origin of the Solar System.

1.1. *Disks in young stars*

In 1965 a young Mexican astronomer speculated that protostars were surrounded by optically thick absorbing material in the form of a torus, and predicted that young stars would show an *IR* excess in their spectra due to star light reprocessed by the relatively colder surrounding material (Poveda 1965). A few years later, another Mexican astronomer confirmed the existence of these *IR* features in the spectra of T-Tauri stars (Mendoza 1968). Since then, the presence of nebular material around young stellar objects has become firmly established, and its signature has been observed into the millimeter region of the electromagnetic spectrum (e.g. Beckwith et al. 1990).

Although very appealing, *IR* and millimeter spectral features do not give information on the shape of the nebulae surrounding the young stellar objects. The race was on to get the first direct image of a circumstellar disk. The main difficulty was attaining

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enough angular resolution: we must remember that a 100 AU feature in the Orion star forming region spans about $0.2''$ as seen from Earth.

The first circumstellar disk to be directly imaged was the one in HL-Tau, observed at $\lambda = 7$ mm using the VLA, by Wilner, Ho, & Rodríguez (1996). After this initial discovery many more followed (see Rodríguez 2000 for a review). To date, observations have established the widespread abundance of disks around young stellar objects.

1.2. *Disks in binary stars*

However, a large fraction of stars in the solar neighborhood are binaries, or part of multiple systems (Duquennoy & Mayor 1991; Heacox & Gathright 1994; Carney et al. 1994). Even among pre-main-sequence stars the binary fraction is as large, perhaps even larger than for main-sequence stars (Mathieu 1994). Now, the presence of a close stellar companion produces an influence whose effects can sometimes be observed, as the circularization of orbits for short period binaries ($P \leq 10$ days). The question then arises: can tidal effects and gravitational perturbations affect the formation of circumstellar disks in binary systems? One way to answer this is by searching for circumstellar disks in binary stars.

In 1994, a circumbinary disk was discovered around the close binary GG-Tau (Dutrey, Guilloteau, & Simon 1994). This binary system has a separation of only $0.25''$ in the sky (~ 38 AU). Its inferred orbital eccentricity is 0.25 and its semimajor axis is 67 AU. The masses of the stars are 0.65 and 0.5 $M_\odot$. The circumbinary disk has an external radius of 800 AU and an inner cavity of 180 AU. The estimated disk mass is 0.17 $M_\odot$. It is clear that the extent of the binary orbit is small compared with the size of the circumbinary disk cavity, and the mass of the disk is small compared with that of the stellar components. In fact, Dutrey et al. (1994) were able to fit a model with Keplerian rotation to their observations.

The first circumstellar disk around a star that is part of a binary system was reported four years later (Akeson, Koerner, & Jensen 1998). The disk was found around the north companion of T-Tauri. The disk was found to have a radius of 41 AU, small compared to the projected separation to the southern companion (100 AU), in which no disk emission could be detected. The estimated disk mass is about 1% of the stellar mass.

In the same year, with only 4 days of difference in the publication date, Rodríguez et al. (1998) announced the discovery of circumstellar disks around both stellar components of a binary system in the *IRS5* source in *L1551*. Both disks are of similar size (~ 10 AU), much smaller than the projected separation of 45 AU between the stars. Again, the disks' masses are very small ($0.06 - 0.03$ $M_\odot$), although these numbers are uncertain by up to a factor of 4, due to possible contamination by free-free emission from ionized gas in the bipolar flow.

The presence of disks in binary stars is now established in many other systems. Trilling et al. (2007), for instance, report observations of 69 A3 to F8 main sequence binaries made with the *IR* satellite *Spitzer*. At $\lambda = 70$ μm they find significant excess emission for 40% of these systems. They also report that a very large fraction (60%) of close binaries (< 3 AU) have excess thermal emission assumed to come from dust disks.

Rodríguez et al. (1998) comment that the millimeter emission of isolated T-Tauri stars is larger than that of those that form part of a binary system with a separation of less than 100 AU. They interpret this as evidence for less massive circumstellar disks in the latter case, presumably due to the gravitational perturbation of the stellar companion.

1.3. *Disks and planetary formation in binary stars*

We know that disks are necessary to form planetary systems. Since, as we have seen, most stars are in binaries or multiple systems, the question arises: can tidal effects and gravitational perturbations inhibit the formation of planets in binary systems? As of February 2008, 270 extrasolar planets and 26 multiple planet systems have been discovered (`http://exoplanet.eu/index.php`). To present, more than 40 planets in binaries or multiple systems are known (Desidera & Barbieri 2007).

A comparison with planets around single stars reveals some differences that suggest an important role for the influence of the stellar companion: the most massive short period planets are all found in binaries (Zucker & Mazeh 2002), and planets orbiting in multiple star systems also tend to have very low eccentricity when their period is shorter than about 40 days (Eggenberger, Mayor, & Udry 2004). It is also interesting to note that planets have been discovered in binaries with separations as small as 20 AU and as large as 6,400 AU (Eggenberger et al. 2004).

2. THE PROBLEM OF THE PLANET IN THE BINARY

From last section, we are left with an intriguing question: How does Nature manage to form planets within binary systems? Planet formation is a very complex phenomenon. It involves dynamics, hydrodynamics, thermodynamics, radiative transfer and chemistry, among others (Hubbard, Burrows, & Lunine 2002; Goldreich 2004; Lissauer 2005).

An easier problem to tackle is: What regions in the phase space of a binary system support trajectories were gas and dust may accumulate? While this is a purely dynamical problem, the answer to this question provides a neccessary, but not sufficient condition, for the formation of disks where planets may arise in binary systems where gravitation dominates over other processes, like gas-dynamics.

Even this relatively "simpler" dynamical problem is not that easy. In a steady-state potential, one searches for the closed, stable and non-intersecting orbits as the loci to park gas and dust in a steady-state configuration. This is the case when the stellar components of the binary system have circular orbits. Unfortunately, the more general case, that of the eccentric binary system, has a potential that varies with time, although in a periodic fashion. It is this quality that can be exploited to tackle the problem, since in this case, one can transform the system into one with a time-independent hamiltonian by adding the time and the original hamiltonian as additional axes in an *extended phase-space* (Lichtenberg & Lieberman 1983). The regular orbits in the new phase space lie on 3-tori, whose intersections with the orbital plane, at times one whole period apart, form a 2-dimensional region. If an additional isolating integral of motion exists, the intersections are then restricted to a 1-dimensional contour (loop) that can be easily spotted. Points in these loops form an ensemble of trajectories that return to the same loop after each whole binary period, although not to the same point (Maciejewski & Sparke 1997). These so-called *invariant loops* can provide the scaffolding to support gas and dust disks in binary systems where the stars follow eccentric orbits, provided they don't intersect with each other.

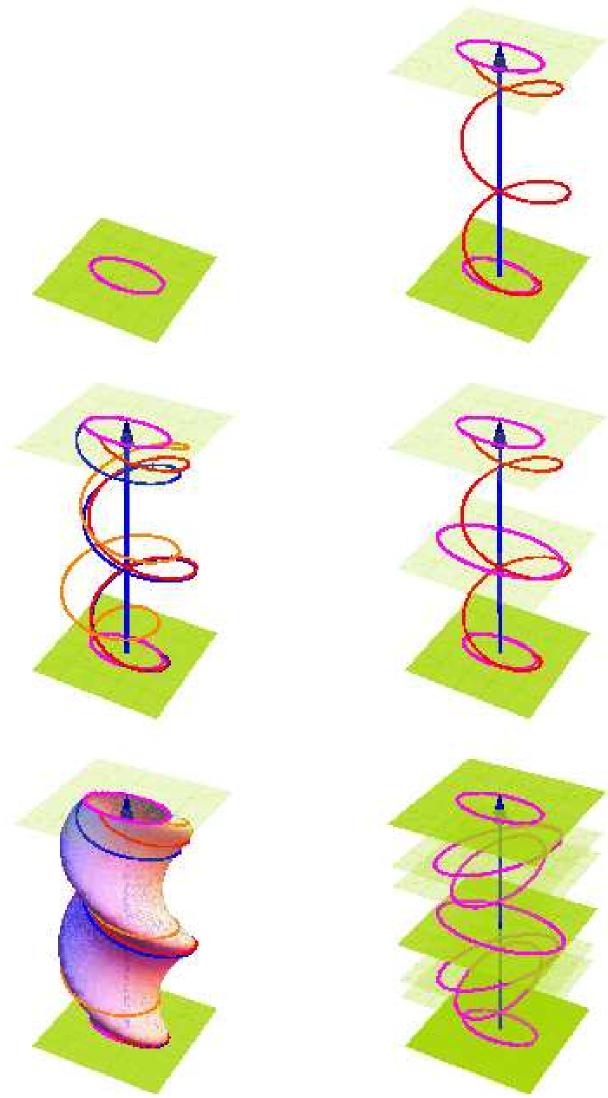

Fig. 1. Illustration of the concept of an invariant loop. The base plane represents the orbital plane at periastron. The vertical axis represents time spanning a whole binary period. Other planes represent snapshots at various binary phases. The helicoidal lines represent trajectories of individual points (see text).

2.1. *Invariant loops: What are they?*

Figure 1 shows a visual illustration of the concept of invariant loops. Let us imagine that at a particular binary phase (e.g. periastron), we trace a closed contour of test particles in the orbital plane (upper left panel). If the contour we choose is an invariant loop, we will see that, as we follow in time the orbit of a particle initially in the contour, it lands in the same contour when we come back to the initial orbital phase, although not on the original point (upper right panel). Indeed, any point in the initial contour has the same property (middle left panel). Now, if we look at the ensemble of points at some other time, we will see that they trace a loop topologically equivalent to the initial one (middle right panel). In fact, the ensemble of all orbits launched from the initial contour define a manifold in the extended phase-space whose cross-section at a given time defines the shape of the contour where the particles lie at a given time (lower left panel). Particles in an invariant loop thus define a closed contour that may change its size, shape and center, but returns

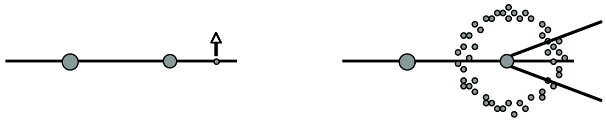

Fig. 2. Illustration of the loop finding algorithm. A test particle is launched at periastron from the line joining the binary components and with an initial velocity orthogonal to this line (left panel). Successive snapshots at subsequent periastra are then plotted (right panel). The radial dispersion for points within a narrow angle is computed as a measure of the 2D extent of the cloud of points. The same particle is then relaunched with a different velocity and the whole procedure is repeated again, until a minimum radial dispersion bellow a threshold value is found (see text).

to the initial contour after each binary period (lower right panel).

The set of non-intersecting invariant loops, if they exist, are the locations where gas and debris can accumulate to form an accretion disk. The concept of invariant loops was originally introduced by Maciejewski & Sparke (1997), within the context of double-bar galaxies.

2.2. *Invariant loops: How to find them?*

Having explained the concept of invariant loops and their importance for the existence of circumstellar and circumbinary disks, the question now is: How do we find invariant loops in the elliptic, planar, restricted three-body problem? The trick is to exploit the fact that particles in invariant loops keep coming back to the same 1-dimensional curve, each time the binary completes a period.

The loop-finding procedure is illustrated in Figure 2. We begin at periastron (apoastron will do too) and look for invariant loops along the line that joins the binary components. At a given position along this line, we launch a test particle with an initial velocity orthogonal to the line. We integrate the orbit forward in time and record the position at successive periastra. Since the combination of initial position and velocity usually is not an invariant loop, the cloud of recorded positions will form a 2-dimensional region. As a measure of its width, we compute the dispersion of radial positions for all that lie within a narrow angle centered at one of the binary components (circumstellar disk) or the binary center of mass (circumbinary disk). The whole procedure is then repeated from the same initial point but with a different velocity. The algorithm is iterated until a minimum in the radial dispersion is found. If this minimum value is below a threshold value set by the

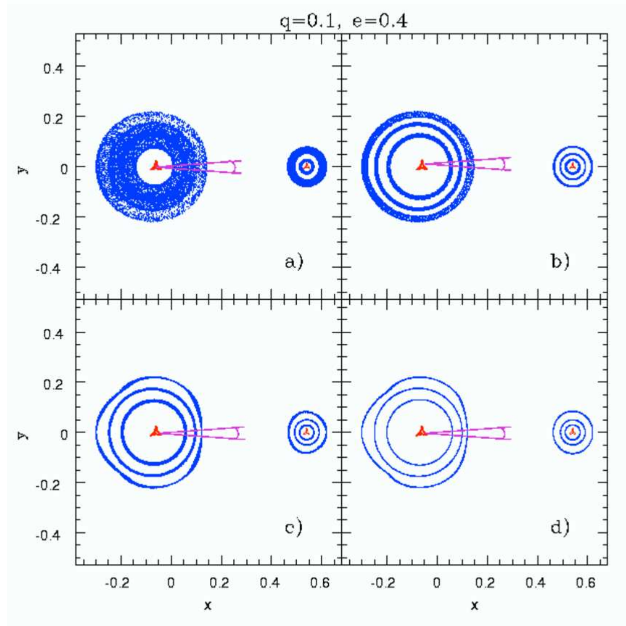

Fig. 3. Loop finding algorithm in action. As we move from the upper left to the bottom right panel, the loop finding algorithm varies the initial velocities until a minimum in the radial spread is found (the figure shows several loops at once).

numerical errors, the cloud of points is considered to be 1-dimensional and the initial position and velocity are recorded as belonging to an invariant loop. We note that our procedure searches for loops that are symmetric about the line joining the two stars only. Other loops may exist but we don't find them. Also, an invariant loop could in principle be unstable, but our method will yield only stable loops. Figure 3 shows this procedure with real loops.

The whole procedure is automated, so the program can sweep the line that joins the binary components, starting from far away in the case of the circumbianry disk, or very close to either star, for the circumstellar disks. At each step the loops are examined to make sure no self-intersections, or intersections with other loops have appeared. When they do, the sweep is terminated and the edge of the respective disk is recorded.

3. RESULTS

A particular case is defined by the mass ratio of the binary components, defined as $q \equiv m_s/(m_p+m_s)$ where $m_p \geq m_s$ are the stellar masses, and the orbital eccentricity e. We have considered the following combinations: $q = 0.001$, 0.1, 0.2, 0.3, 0.4 and 0.5, and $e = 0$, 0.2, 0.4, 0.6 and 0.8 (Pichardo, Sparke, & Aguilar 2005).

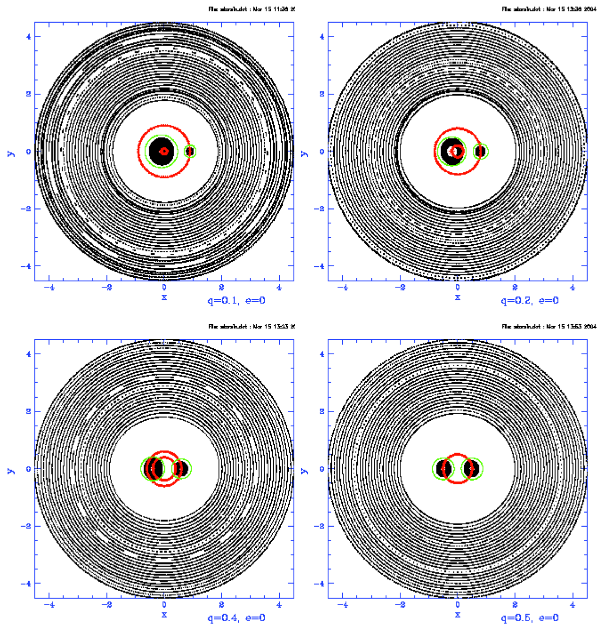

Fig. 4. Circumbinary disk for circular cases. The mass ratios are 0.1, 0.2, 0.4 and 0.5, from top left to bottom right panels. The red lines are the orbits of the stars. The size of the green circles are the Jacobi radius.

3.1. *The circular case*

Figure 4 presents the results for the circumbinary disks for four different stellar mass ratios. The red lines are the individual stellar orbits while the green lines indicate regions around each star whose radii are the Jacobi radius. It is clear that the size of the central gap is largely unaffected by the change in mass ratio. Figure 5 presents the same cases, but in an expanded scale, to show in detail the circumstellar disks. Here the picture is different; the size of the circumstellar disks is affected by the mass ratio, although it is consistent with their Jacobi radius.

3.2. *The elliptic case*

The elliptic case is quite different. Figure 6 shows the circumbinary disk for four different eccentricities when the stellar masses are equal. We see that the size of the central hole of the circumbinary disk increases out of proportion to the size of the stellar orbits, as the eccentricity increases. Figure 7 shows the corresponding circumstellar disks. Again, the disks shrink by a large factor as the eccentricity increases. The same behaviour is present at other mass ratios.

3.3. *Some specific cases*

Our experiments have allowed us to find interpolating formulae that allow us to predict the size of the circumstellar disk and that of the central gap in the circumbinary disk, as a function of stellar mass

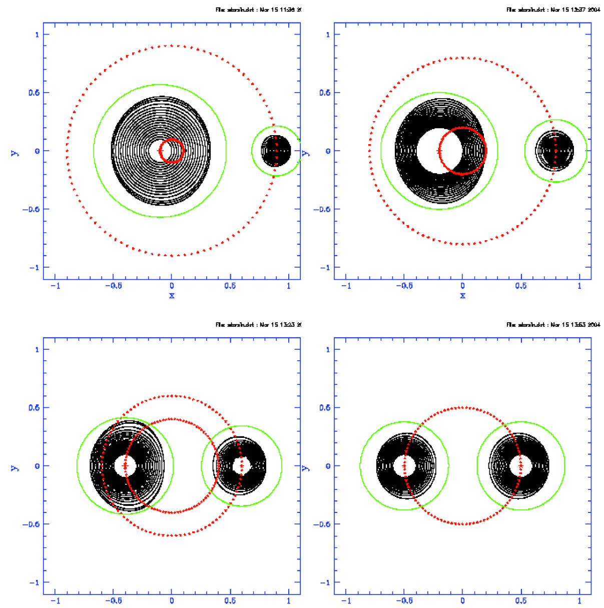

Fig. 5. Circumstellar disks for circular cases. The same cases as in Figure 4 are presented. The colored lines are also the same.

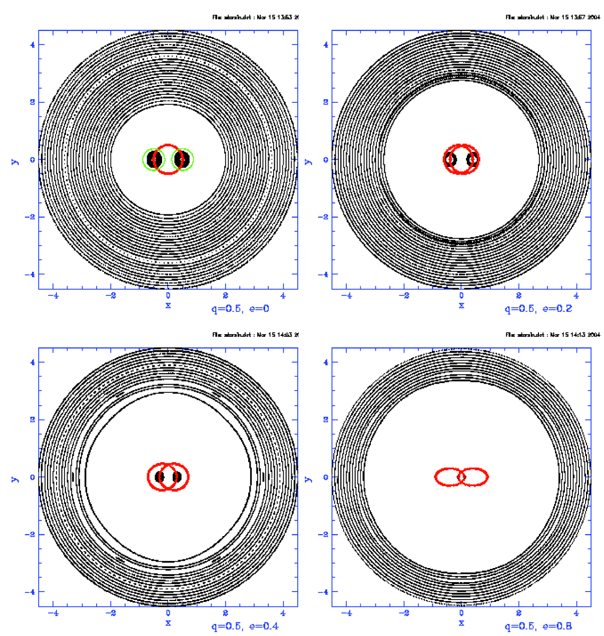

Fig. 6. Circumbinary disk for equal stellar masses and e = 0, 0.2, 0.4 and 0.8, from top left to bottom right panels. The red lines are the stellar orbits. The green circle has the Jacobi radius for the circular case.

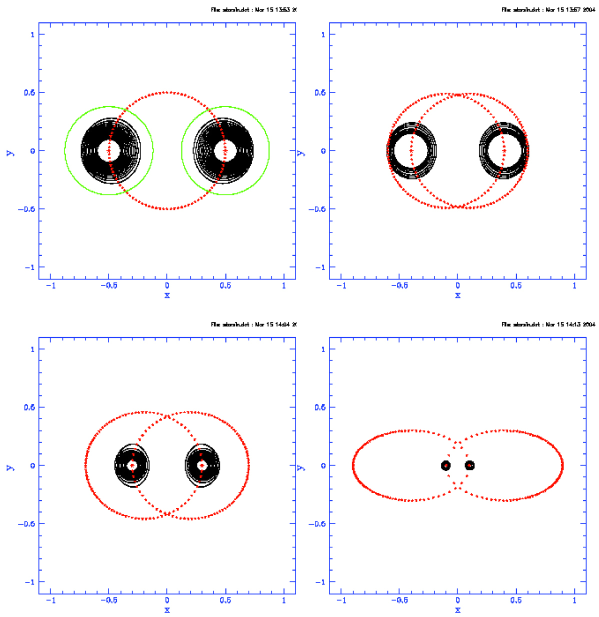

Fig. 7. Circumstellar disks for elliptical cases. The same cases as in Figure 6 are presented. The colored lines are also the same.

ratio and eccentricity (Pichardo et al. 2008). We use these results to tackle some specific cases.

3.3.1. *IRS5 in L1551*

Rodríguez et al. (1998) found that the size of the circumstellar disks are about the same and equal to ~ 10 AU, while their projected separation is 45 AU. Observations in the millimeter range suggest there is an outer, elongated structure of dust and gas that may be a circumbinary disk (Keene & Masson 1990). The observed properties of the stars limit the stellar mass ratio to $0.4 \leq q \leq 0.5$. We have considered several eccentricities at these mass ratios and found that when $e > 0.2$, the predicted circumstellar disk sizes shrink below the observed value. We conclude that the orbital eccentricity in this case must be smaller than or equal to 0.2.

3.3.2. α *Centauri A & B*

This binary system consists of a $G2V$ star (1.1 $M_\odot$) and a KIV star (0.9 $M_\odot$), with an orbit with a semimajor axis is 23.4 AU and an eccentricity of 0.52 (See 1893; Heintz 1982). The large eccentricity of this system makes it a test case to see the limits for planetary formation in close and eccentric binary systems, and thus it has been extensively studied. Holman & Wiegert (1999) have surveyed stable regions directly integrating planetary orbits. They find stable orbits up to 3 AU from the stars, or from 70 AU outwards for circumbinary orbits. Quintana et al. (2002) have studied planet formation in this system and found stable prograde orbits within 2.5 AU of either star. Our results indicate that a circumstellar disk can exist up to 3 AU of the primary and up to 2.3 AU of the secondary star. The circumbinary gap has a radius of 80 AU.

3.3.3. *GG-Tau*

GG Tau is a young multiple stellar system composed of two binaries: GG Tau Aa/AB and GG Tau Ba/Bb. The first one has a circumbinary disk that has been resolved at millimeter (Guilloteau, Dutrey, & Simon 1999), optical (Krist, Stapelfeldt, & Watson 2002) and near IR (Roddier et al. 1996) wavelengths. The central gap has a radius between 180 and 190 AU (Duchéne et al. 2004). The orbital parameters of the binary are controversial: McCabe, Duchne, & Ghez (2002) deduce a semimajor axis of 35 AU and an orbital eccentricity of 0.3, while Itoh et al. (2002) propose 50 AU and 0.4–0.5, respectively. The mass ratio is 0.47 (White et al. 1999).

Taking a central gap of 180 AU and a stellar mass ratio of 0.47 as fixed, we have determined a region of possible solutions for this system in the semimajor axis *vs* eccentricity plane, assuming that the central binary is the only one responsible for the disk gap. Our solutions restrict the semimajor axis to $50 \leq a \leq 85$ AU, with high-eccentricity solutions favoring the lower range, while low-eccentricity cases the higher range in a. Our solutions are compatible with those of McCabe at al. (2002) for $e = 0.3$ and $a \sim 55$ AU. Compatibility with those of Itoh et al. (2002) requires a larger eccentricity $e = 0.4 - 0.5$ with a slightly smaller semimajor axis: $a \sim 50$ AU. A way to break the ambiguity and pin down a unique solution requires a determination of the offset of the gap center with respect to the barycenter of the binary.

4. CONCLUSIONS

A large fraction of stars are born as part of binary or multiple systems. Circumbinary and circumstellar disks have been found in young binary systems. Furthermore, a good fraction of extrasolar planets found so far orbit binaries, or stars that are part of binary systems. Although some differences between planets moving around isolated stars and those in binary systems have been found, it is clear that planet formation is a widespread phenomenon, not inhibited by the presence of a stellar companion.

This poses a theoretical challenge to find the regions in the phase-space of a binary where stable, non-intersecting orbits may exist, since it is on these orbits where presumably a circumbinary or circumstellar disks may exist.

We used the concept of *invariant loops* to plumb the phase-space of the restricted, elliptical, three-body problem and determined the regions spanned by stable, non-intersecting invariant loops, as a function of stellar mass ratio and orbital eccentricity.

Our results indicate that, as the orbital eccentricity increases, the size of the central gap in the circumbinary disk grows and the extent of the circumstellar disks shrink dramatically. This strong dependency allow us to place limits on observed systems where the size of the circumstellar disks, or that of the central gap in the circumbinary disk, are known in relation to the stellar component separation.

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