PROCEEDINGS OF SCIENCE

PoS(MULTIF15)019

Pre-main sequence interacting binaries. An appraisal of the state of the field.

Ana I. Gómez de Castro
AEGORA Research Group, Universidad Complutense de Madrid
Fac. de CC Matemáticas, Plaza de Ciencias 3, 28040 Madrid, Spain
E-mail: aig@ucm.es

Pablo Marcos-Arenal
AEGORA Research Group, Universidad Complutense de Madrid
Fac. de CC Matemáticas, Plaza de Ciencias 3, 28040 Madrid, Spain
E-mail: pablmarc@ucm.es

A fraction of the pre-main sequence (PMS) binaries are close binaries with orbital semimajor axis smaller than 0.2 AU and orbital periods shorter than 100 days. In these systems, stable *circumbinary (CB) disks* are observed. The inner radius of CB disks is about 2-3 times the semi-major axis of the orbit creating a large cavity that contains the stars' orbit. Transient structures, shock waves and *circumstellar (CS) disks* are formed within it. In this contribution an appraisal of the current status of the research in this field is presented.

Keywords: Stars: Pre-main sequence - Stars: Interacting binaries.

XI Multifrequency Behaviour of High Energy Cosmic Sources Workshop
25-30 May 2015
Palermo, Italy

1. Introduction

This article is a brief summary of the invited review talk on pre-main sequence (PMS) binaries presented during the Workshop *XI Multifrequency Behaviour of High Energy Cosmic Sources* held in Mondelo (Italy) in 2015. The workshop is a multidisciplinary forum around the physics and the observations of high energy sources hence, interacting binaries are addressed in depth. PMS close binaries are a new comer to the field. In the past (see the conference series), magnetic activity, jets and accretion shocks in PMS stars have been addressed. In this paper, the stress is made in PMS binaries, as members of the spectroscopic binaries zoo. For this reason, aspects as their use to constrain PMS evolutionary tracks (see *i.e.* Torres et al. 2013) will not be treated.

In Section 2, the route to the formation of PMS binaries is outlined. In Section 3, we review the characteristics of PMS close binaries in the generic context of spectroscopic binaries (SB) (Pourbaix et al., 2004). In Section 4, the current status of the numerical modelling of the systems is described. A final summary on the relevance of PMS binaries for star formation studies closes the article (Section 5).

2. The formation of PMS binaries

The formation of multiple stellar systems is a natural result of molecular clouds fragmentation. The joint action of gravity and turbulence leads to the concentration of mass in dense filaments that later fragment to form protostellar cores undergoing gravitational collapse. The observed distribution of the fragments (mass, size, distance, gravitational coupling) is well modelled by numerical simulations. They predict the formation of a large fraction of binaries and multiple systems, in good agreement with the observed phenomenology (Bate 2009, Offner et al. 2010, Joss et al., 2012). Even very simple models, such as 3D smooth particle hydrodynamics (SPH), provide good results (Bate, 2009-2012). Further refinements take into account the magnetohydrodynamic (MHD) nature of turbulence in star forming regions and show that misalignments between the magnetic field and the angular momentum orientation in the fragments favour binary formation (Joss et al., 2012; Boss & Keiser, 2013). The large number of free parameters in the simulations allows that *all models* are able to reproduce the observed distribution of wide binaries and multiple systems (see the recent review by Reipurth et al., 2014), in spite of the different physical scenarios. From the physics standpoint, this indicates that there are many plausible physical routes to cloud fragmentation leading to the observed configuration.

The fraction of binaries is observed to decrease during pre-main sequence (PMS) evolution (see *i.e.* Connelley et al. 2008). After fragmentation, the non-homologous gravitational collapse leads to a differentiation between the stellar embryo and the surrounding envelope. Young Stellar Objects (YSOs) are declared to be class 0 sources when the central source contains about half of the mass of the fragment. Binaries and multiple systems are frequent among class 0 sources. The stellar birthline is defined by the end of this main infall phase. After that, the accretion flow is transported via the Keplerian disk. The luminosity of the disk varies by several orders of magnitude during PMS evolution. At the first stages (so-called class I YSOs), the stellar atmosphere is veiled by the radiation from the disk and occulted by the accretion flow and the remnant extinction of the envelope. As these decrease, the stellar atmosphere becomes recognisable (class II YSOs). Finally, the young planetary disk is formed and the stellar evolution is decoupled from the disk evolution (class III YSOs). Hence, class I, II and III YSOs trace the evolutionary state of the disk.

The interaction with the circumstellar (CS) environment as well as the dynamical interaction with other PMS stars lead to mergers or escapes, decreasing the fraction of binaries with intermediate separations (1,000- 4,500 AU) from Class 0 to Class III YSOs. A good example comes from the study run by Connelley et al. (2008), as shown in Figure 1, the fraction of binaries decreases from about 50% in Class 0 sources to less than 5% in Class III sources.

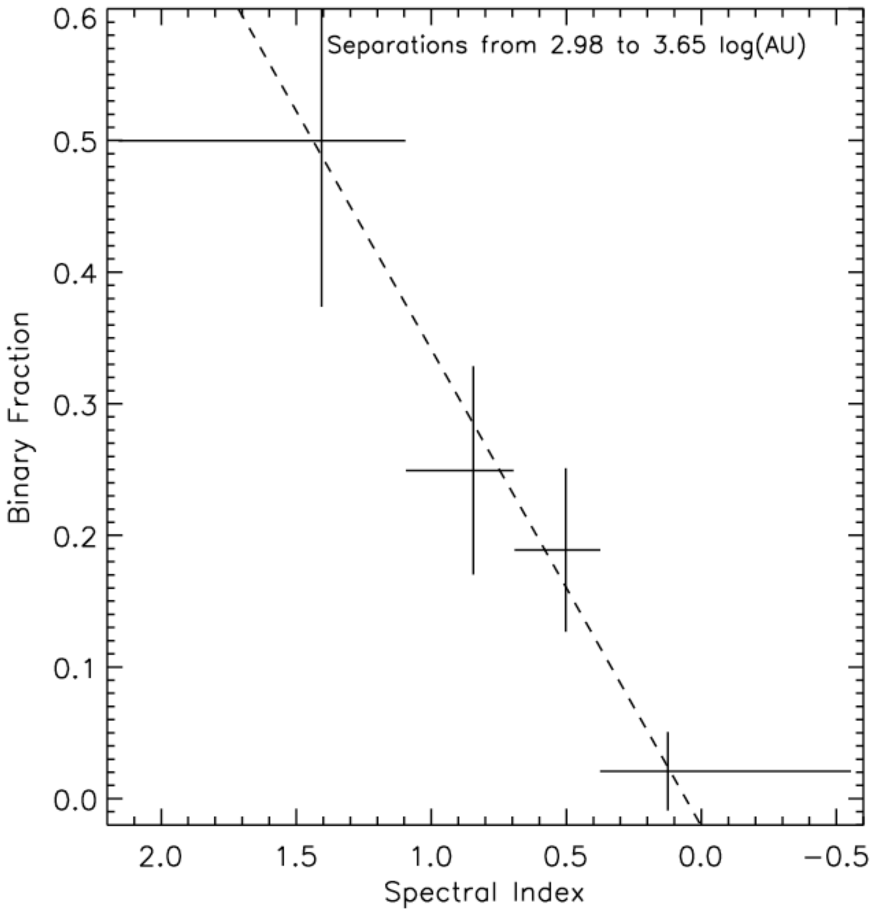

Figure 1: The evolution of the binary frequency at separations from 963 AU to 4469 AU (2.98 to 3.65 log(d/1 AU)) versus spectral index; the spectral index varies from 1.5 to 0 as the PMS stars evolve from Class 0 to Class II. The dotted line is a linear fit to the data showing the decline of the binary frequency at wide separations with respect to spectral index. The decline is remarkably steady (from Connelley et al. 2008).

Circumbinary (CB) disks are observed around close binary PMS systems; they do channel the accretion flow onto the stars. The interaction between the young binaries and the CB disk is a rich source of physics somewhat reminiscent of the common envelope phase during the late stages of close binaries evolution. The angular momentum budget in PMS binaries has a significant contribution from the CB disk (including spiral density waves) and the accretion streamers that channel the material from the CB disk onto the stellar surfaces. A generic configuration is shown in Figure 2; the orbit of the binary excavates a large inner hole in the CB accretion disk. The hole is filled with transient dusty structures that transport the material from the inner border of the disk onto the stars. For some specific orbital parameters (see Section 4) CS disks are formed around each component, within the Roche Lobe. Angular momentum transport along the streamers dominates the evolution of the PMS binaries; according to numerical simulations, streamers may carry as much as a 30% of the total accretion flow (Shi et al., 2012). When magneto-turbulent stresses are considered, the flow through the accretion streams increases significantly (McFadyen & Milosavljevic, 2008).

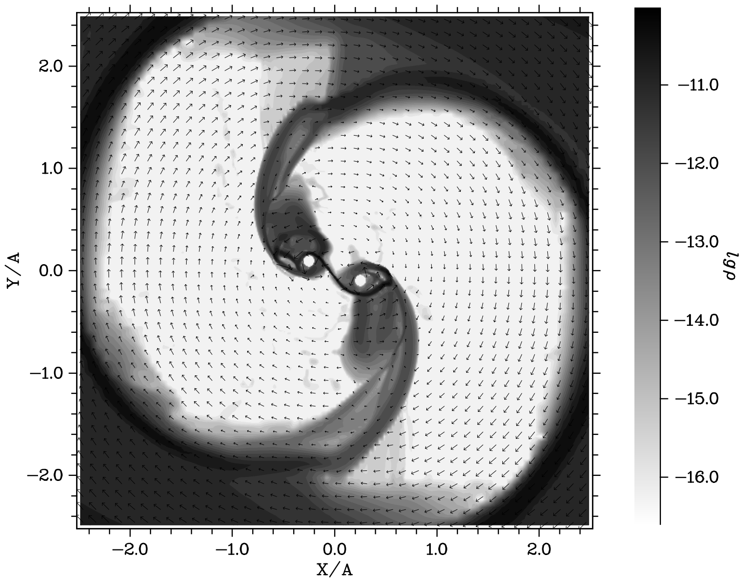

Figure 2: Generic configuration of matter distribution in a PMS close binary. The stellar orbit creates a large gap within the CB disk and matter is channelled onto the stars by the variable gravitational field generated by the binary orbit. Most of the matter is transferred through streamers that connect the inner border of the CB disk to the stars. CS disks are accommodated within the Roche lobe. If the mass of the components is significantly different, only the CS disk of the primary remains estable (from Gómez de Castro et al. 2013).

In practice, the redistribution of angular momentum in the system is controlled by two opposing terms: the spin-up by accretion and the spin-down torque associated with the non-axisymmetric disk/accretion streamers. Unfortunately, numerical modelling is very sensitive to the uncertainties in the accretion disk thermodynamics (and very sensitive to numerical inaccuracies). In this sense, PMS close binaries are interesting objects for interactive binaries research. In these systems, the angular momentum stored in the binary orbit is transferred to the common envelope, possibly leading to stellar mergers and Supernova explosions. During the PMS evolution of close binaries, angular momentum is transferred from the CB disk onto the stars during the early phases and back to the young planetary disk as the stars evolve. It is worth noticing that the predictions of the equilibrium tide theory are fulfilled by PMS close binaries (Melo et al. 2001), *i.e.* close binary orbits circularize during the Hayashi phase (Zahn & Bouchet, 1989) while the stars are still fully convective, roughly during the first 10 Myr of a solar type star. However, the CB disk is a significant angular momentum repository during this phase.

3. PMS close binaries in context: main characteristics

The compilation by Melo et al. 2001 includes 40 PMS spectroscopic binaries (SB) with known orbital elements. There have been few additions since then: RX J0528.9+1046 and RX J0529.3+1210 (PMS-SB belonging to Class III also named weak line TTSs or WTTS, from Torres et al. 2002), HBC 408 (WTTS from Griffin 2009), HBC 427 (WTTS from Simon et al. 2013), V1852 Ori (WTTS from Ruiz-Rodriguez et al. 2013), HD 34700 (PMS-SB beloging to Class II, also named classical TTS or CTTS, from Torres 2004), V582 Mon (WTTS, Johnson et al. 2004) and CS Cha (CTTS, Guenter et al . 2007).

Most of the PMS-SBs are low mass systems with primary spectral type G0 or later. There are only a handful of PMS-SB that belong to Class II, namely V4046 Sgr, AK Sco, DQ Tau, UZ Tau E with orbital period shorter than 20 days, GW Ori with period 241.9 days and CS Cha with period longer than 2482 d (Guenter et al. 2007). Most PMS-SBs are rather evolved objects containing very active young stars (WTTSs) surrounded by thin disks (often debris disks). In Figure 3, all these sources are plot in an eccentricity versus period diagram; circularised orbits are observed only in short period sources. Note also that CTTS SBs, the youngest of the PMS-SBs, are not concentrated in any area of the diagram.

The rather small number of known PMS-SBs results from the main sites of star formation being located further than 140 pc from the Sun; the ring of molecular clouds that surrounds the Sun ranges from a distance of ∼140 pc (Taurus, Auriga, Chamaleon, Ophiuchus...) to 450 pc (Orion). Hence, it is difficult to measure precise radial velocities for these low-mass stars with the traditional high resolution optical spectroscopy. Successful attempts have been carried out using large aperture telescopes in the infrared (Prato 2007).

In the last few years, some radial velocity surveys have been run over the main star formation complexes to identify suitable candidates for follow-up studies. Tobin et al. (2009) used the multifiber echelle spectrograph in the 6.5 m MMT and Magellan telescopes to obtain multi epoch radial velocity observations of 727 objects in the Orion nebula cluster and identified 74 new close binaries for which orbital elements are not known, unfortunately. Later on, Nguyen et al. (2012) carried out a similar survey in the Chamaleon I and Taurus-Auriga star forming regions identifying three new PMS-CBs and two close triplets.

These new sources share photometric properties with the known PMS-SBs (see Figure 4). PMS stars are characterised by excess radiation (with respect to their main sequence analogues) in all spectral bands (see Gómez de Castro 2013, for more details). The infrared excess is caused by the CS disks that during Class 0-II phases release in this range the energy generated in the disk by the accretion process. During the Class III phase, the passive disk reprocess the stellar radiation into the infrared also inducing an infrared excess though milder. The main photometric characteristic of PMS close binaries is a drop in the near infrared excess when compared with their single analogues (see *i.e.* Mathieu et al 1994). The gravitational action of the orbiting stars shifts outwards the disk inner radius. The orbit clears out a gap of radius $\sim 2-3$ times the semimajor axis of the orbit. The inner disk is the major contributor to the *near infrared* excess. In Figure 4, the best fitting regression line is represented for new PMS close binaries identified by the surveys

PoS(MULTIF15)019

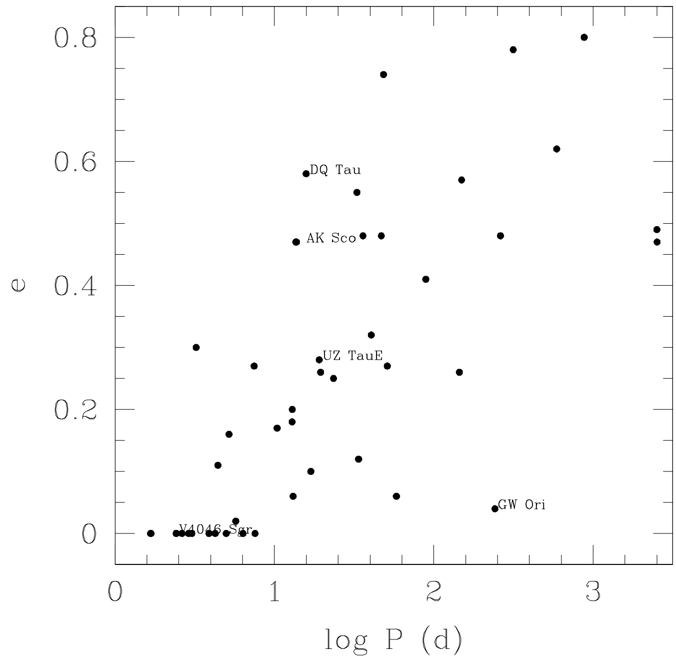

Figure 3: Eccentricity versus period plot for PMS SB with known orbital parameters.

Table 1: Fits to PMS-SBs groups

Description	PMS-SBs	
	known orbits	from radial velocity surveys
Slope	1.05	1.07
Intercept	0.36	0.40
R value	0.632	0.597
P value	3.5799e-5	3.7870e-5
σ	0.2209	0.2291
χ^2	1.8196	1.2245

and compared with the characteristics of the already known systems with well determined orbital parameters (see Table 1 for the numerical coefficients[1]. We conclude that both data samples come from the same distribution with probability 72.86% (KS test: 0.1524).

The main catalogue of galactic SBs, the S_{B^9}, has been compiled by Pourbaix et al. (2004) and

[1]For the calculation, the three reddest PMS-SBs detected by radial velocity surveys have been neglected to avoid biasing the results.

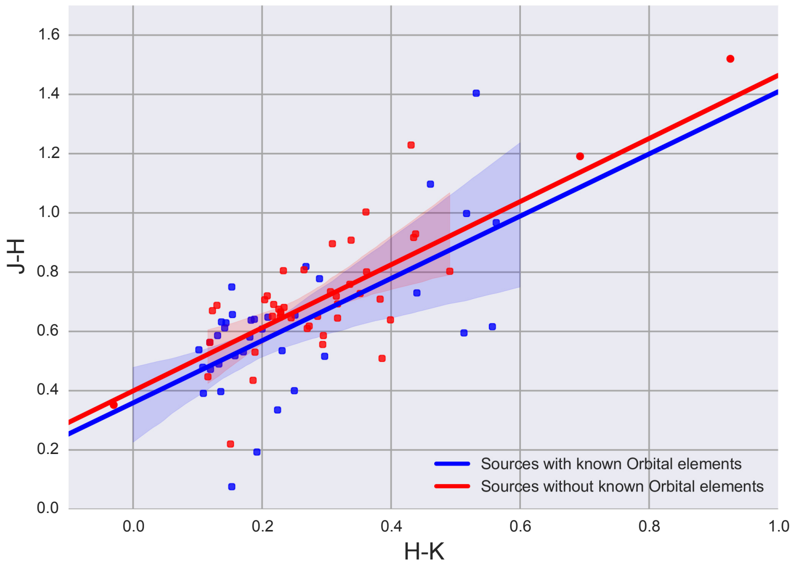

Figure 4: Comparison between PMS-SBs with known orbital elements and the close binary systems detected in radial velocity surveys. The linear regression lines are represented for both of them (see text).

it is made available to the community through the services of the Centre de Données astronomiques de Strasbourg. A signficant fraction of the SBs has been detected by the infrared 2MASS survey allowing to compute the J-H and H-K colours for them. As shown in Figure 5, galactic SBs are mainly main sequence stars. The PMS-SBs are cool compared with the galactic average; most systems are composed by low mass stars. Note also that some of them display significant infrared excess, especially those detected by the radial velocity survey in Orion (Tobin et al. 2009). In fact, some of them could be just reddened field close binaries.

4. Numerical models of close PMS binaries evolution

In close PMS systems, accretion disks can either take up or release angular momentum and the details of evolution depend on the mass ratio between the two stars and on the orbit eccentricity (Artymowicz & Lubow, 1994, Bate & Bonnell, 1997, Hanawa et al., 2010, de Val Borro et al., 2011, Shi et al., 2012). Highly eccentric orbits favour the formation of spiral waves within the inner disk that do channel the flow as the accreting gas streams onto each star. In this framework, PMS binaries represent a special kind of interacting binaries where the circumbinary disk mediates in the star-star interaction as a continuous supply of angular momentum (and matter) to the system.

Numerical simulations of the evolution of disks around PMS binaries point out that an inner gap develops within the circumbinary disk; the gap radius is about 2-3 times the semi-major axis of the orbit. The characteristics of the gap depend on the binary mass ratio, for instance, for secondary to primary mass ratios $q << 1$, the gap becomes an annular ring around the primary through which the secondary travels. It also depends on the relative mass of the secondary to the protostellar disk; if the disk mass is large compared to the mass of the secondary, inward orbital migration of

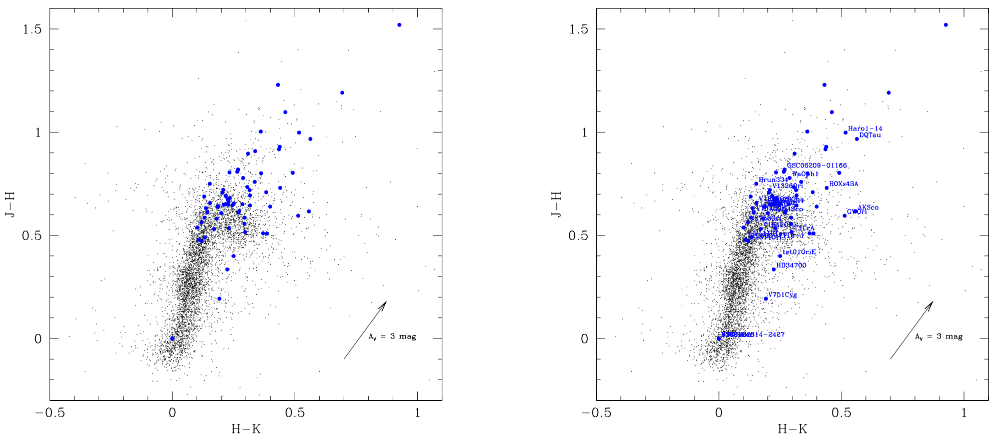

Figure 5: Known spectroscopic binaries in a J-H, H-K infrared colours diagram. Small black dots represent the systems included in the S_{B^9} and big blue dots the known PMS SBs. *Left:* All PMS-SBs are plotted. *Right:* The PMS-SBs with known orbital elements are labelled.

the secondary may occur on time scales comparable to the disk accretion time scale, eventually leading to collision (Lin & Papaloizou, 1993). There have been extensive theoretical studies of this situation, using both analytic and numerical methods (e.g., Goldreich & Tremaine, 1980; Lin & Papaloizou, 1986; Nelson & Papaloizou, 2003).

For $q \simeq 1$, up to three disks may be formed in the system as illustrated in Fig. 6 for the AK Sco system (Gómez de Castro et al., 2013). The structure of the gas flow obtained from the HD simulations consists of a circumbinary disk, a gap, circumstellar accretion disks, and a system of shock waves and tangential discontinuities. These elements are outlined in the Figure 6. Note that in the inner region of the circumbinary disk the velocity distribution is non-Keplerian and gas motion is governed by bow shocks, one per star, and binary component's gravity wells. The size and the shape of the gap are substantially determined by the bow shocks.

The system works like a gravitational engine that efficiently extracts energy from the inner disk border to release it onto the sources of the gravitational field. Figure 7 displays the evolution of the inner region of the computational domain during a single orbital period. The AK Sco binary system has a substantially elliptical orbit which results in an interesting phenomenon. When the system approaches periastron, the outer boundaries of the circumstellar disks (and the accretion streams passing by) get close enough one to each other to effectively lose the angular momentum, leading to an increase of the accretion rate by a factor of 2-3. A tangential discontinuity is produced at the point where the primary and secondary accretion flows get in contact because, at the interface between them, the matter orbiting around the primary moves in the opposite direction that the matter orbiting the secondary. Collisional heating, development of instabilities (like Rayleigh-Taylor instability on the interface), shock wave formation will efficiently remove the angular momentum and, henceforth, lead to an accretion outburst.

In general, numerical studies have found that the radius of the disk inner edge depends on several factors, including the binary separation, mass ratio, eccentricity, and the strength of the

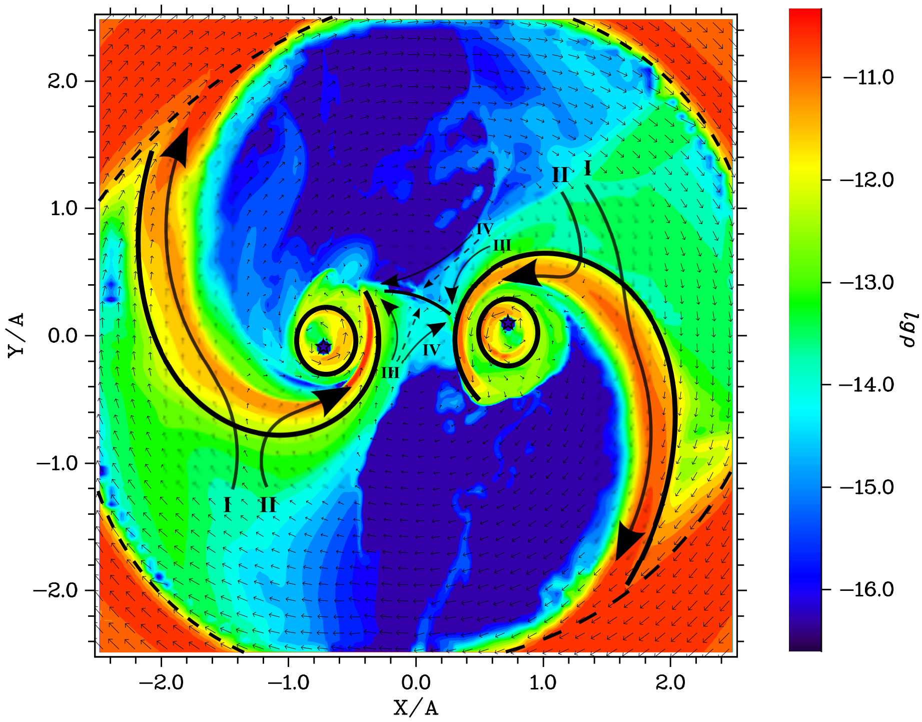

Figure 6: The orbit of the binary (for q $\simeq$ 1) creates an inner gap in the circumbinary disk. The main dynamical features within the gap are outlined: (I) - the outflow to the circumbinary envelope; (II) - the accretion stream; (III, IV) - parts of accretion streams that form the inner stationary shock wave and contribute to the accretion rates. The dashed line indicates the boundary of the gap. Note that the arrows mark the direction of the flow in the bow shock (from Gómez de Castro et al., 2013).

disk turbulence (Artymowicz & Lubow, 1994). Both SPH and grid (HD or MHD) simulations show that the flow rate through the gap depends on the binary and the disk properties. Almost all studies have adopted the α-prescription to describe the angular momentum transport in the disk. Some attempts have been made to implement in a self-consistent manner the turbulence generated by the magneto rotational instability (MRI). As shown by Shi et al. (2012) because the MHD stresses are more efficient at introducing matter into the gap, the total torque per unit disk mass rises significantly (about 14 times larger than found in HD simulations). In general, the accretion rate appears to be smaller in circumbinary disks than in protostellar disks around single stars due to the presence of the binary torque, (e.g., Lubow & D'Angelo, 2006).

Unfortunately, these detailed simulations are not easy to contrast with data given the scarce access to facilities working in the ultraviolet (UV) range; The spectral indicators most sensitive to accretion and to the CS environment are in this range. Very few monitoring campaigns have been run on these systems; only AK Sco (Gómez de Castro et al. 2013, 2016a) and DQ Tau and UZ Tau (Ardila et al. 2015) have been monitored. As a result, numerical modelling is lacking of basic data to understand the physics of these systems. For instance, numerical simulations of AK Sco predict a changing environment from orbit to orbit caused by the chaotic nature of the equations that shows in the variations of the observed accretion rate between subsequent periastron passages (Gómez de Castro et al. 2016b). Therefore, accretion rate enhancements are subjected not only to

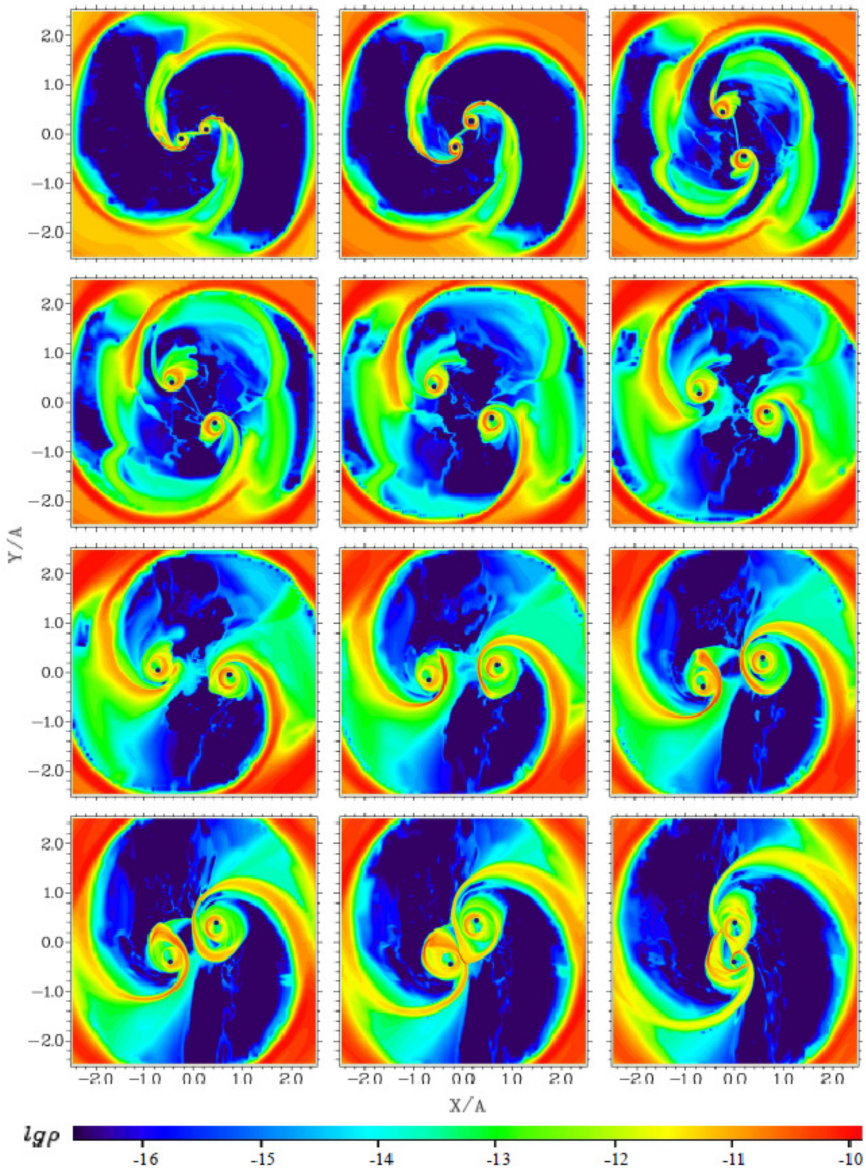

Figure 7: Evolution of the inner region of computational domain during a single orbital period for the PMS close binary AK Sco with eccentricity of 0.47 (from Gómez de Castro et al., 2013).

the characteristics of the orbit but also to the environmental conditions that may change from orbit to orbit.

5. Summary

The number of known PMS close binaries is increasing providing an ideal laboratory for the study of binary interaction with circumbinary disks. The numerical modelling of the systems is however, hampered by its sensitivity to the uncertainties of the thermodynamics of protostellar disks. Research on PMS close binaries ought to provide fundamental clues on the operation of gravitational torques during protostellar disks evolution.

There are many more aspects making of PMS close binary an interesting laboratory and that have not been addressed in this work. For instance, a key element in PMS evolution is the interaction between the stellar magnetosphere and the inner border of the CS accretion disk (see Gómez de Castro, 2013 for a recent review on the subject). The observational study of this interface is complex since it shares spectral signatures with the outflow and the inner border of the disk. CS disks in PMS close binaries are very small structures that survive within the Roche lobe providing a significantly cleaner environment to study the disk-magnetosphere locking. In addition, the accretion rate is not constant but significantly enhanced at periastron passage, allowing to single out accretion events (see Ardilla et al. 2015, Gómez de Castro et al. 2016a). An additional source of interest in the study of close binary systems relates with the formation and evolution of exoplanetary systems hosting the so-called hot Jupiters. Close binaries with low mass ratio[2], such as UZ Tau, provide important clues on giant planets formation and migration.

Acknowledgements: The authors acknowledge support from the Ministry of Economy and Competitiveness of Spain through grants AYA2011-29754-c03-01 and ESP2014-54243-R.

References

Ardila, D.R., Johns-Krull, C., Herczeg, G.J. et al. 2015, ApJ, 811, 131

Artymowicz, P., Lubow, S.H. 1994, ApJ, 421, 651

Bate, M.R., Bonnell, I.A. 1997, MNRAS, 288, 1041

Bate, M.R., 2009, MNRAS, 419, 3115

Bate,M.R., 2012, MNRAS, 392, 1363

Bianchi, L., Herald, J., Efremova, B. et al. 2011, Ap&SS, 335, 161

Boss, A.P., Keiser, S.A. 2013, ApJ, 770, 51

Chen, X., Arce, H.G., Zhang, Q., et al. 2013, ApJ, 768, 110

Connelley, M. S. et al. 2008, AJ, 135, 2496

Covino, E., Melo, C., Alcala, J.M., et al. 2001, A&A, 375, 130

Duquennoy, A., Mayor, M. 1991, A&A, 248, 485

Gómez de Castro, A.I., ApJ, 698, L108

Gómez de Castro, A.I., López-Santiago, J., Talavera, A. et al. 2013, ApJ, 766, 62

[2]The mass ratio, q, is defined as $q = M_2/M_1$, being M_1, the mass of the primary and M_2, the mass of the secondary.

PoS(MULTIF15)019

Gómez de Castro, A.I. 2013, Planets, Stars and Stellar Systems Vol. 4, by Oswalt, Terry D.; Barstow, Martin A., ISBN 978-94-007-5614-4. Springer Science+Business Media Dordrecht, 2013, p. 279

Gómez de Castro, A.I., Loyd, R.O.P., France, K. et al, 2016a, ApJ, 818, L17

Gómez de Castro, A.I., Loyd, R.O.P., France, K. et al, 2016b, ApJ, submitted.

Griffin, R.F., 2009, Observatory, 129, 317

Goldreich, P.,S., Tremaine, S., 1980, ApJ, 241, 425
Guenter, E.W., Esposito, M., Mundt, R., et al. 2007, A&A, 467, 1147

Hanawa, T., Ochi, Y., Ando, K., 2010, 708, 485

Johnson, J.A., Marcy, G.W., Hamilton, C.M., et al. 2004, AJ, 128, 1265

Joos, M., Hennebelle, P., Ciardi, A. 2012, A&A, 543, 128

Lin, D.N.C., Papaloizou, J.C.B. 1993, Protostars and planets III (A93-42937 17-90), p. 749-835

Lubow, S.H., D'Angelo, G., 2006, ApJ, 641, 526

Mathieu, R.D. 1994, ARA&A, 32, 465

Melo, C.H.F., Covino, E., Alcala, J.M., et al. 2001, A&A, 378, 898

Nelson, R.P., Papaloizou,J.C.B., 2003, Proceedings of the Conference on Towards Other Earths: DARWIN/TPF and the Search for Extrasolar Terrestrial Planets, 22-25 April 2003, Heidelberg, Germany. Edited by M. Fridlund, T. Henning, compiled by H. Lacoste. ESA SP-539, Noordwijk, Netherlands: ESA Publications Division, ISBN 92-9092-849-2, 2003, p. 175 - 186

Nguyen, D.C., Brandeker, A., van Kerkwijk, M. H. et al., 2012, ApJ, 745, 119

Offner, S.S.R., Kratter, K.M., Matzner, C.D. et al. 2010,ApJ, 725, 1485

Pourbaix D., Tokovinin, A.A., Batten A.H., et al. 2004, A&A, 424, 727

Prato, L., 2007, ApJ, 657, 338

Reipurth, B., Clarke, C.J., Boss, A.P. et al. 2014, Protostars and Planets VI, Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning (eds.), University of Arizona Press, Tucson, 914 pp., p.267-290

Ruiz-Rodríguez, D. Prato, L., Torres, G. et al., 2013 AJ, 145, 162

Simon, M., Schaefer, G. H., Prato, L., et al., 2013, ApJ,773, 28

Shi, J.-M., Krolik, J.H., Lubow, S.H. et al. 2012, ApJ, 749, 118

Stahler, S.W., 2010, MNRAS, 402, 1758

Tobin, J. J., Hartmann, L., Furesz, G. et al., 2009, ApJ, 697, 1103

Torres, G. et al., 2002, ApJ, 123, 101

Torres, G., 2004, AJ, 127,1187

Torres, G., Ruiz-Rodriguez, D., Badenas, M. et al. 2013, ApJ, 773, id40

de Val-Borro, M., Gahm, G. F., Stempels, H. C, et al. 2011, A&A, 535, 6

Zahn, J.P., Bouchet, L., 1989, A&A, 223, 112