Mem. S.A.It. Vol. 88, 587

Memorie della

The early evolution of solar-type stars: accretion, magnetism, and star-disk interaction

J. Bouvier

Univ. Grenoble Alpes, CNRS, IPAG, F-38000 Grenoble, France
e-mail: `jerome.bouvier@univ-grenoble-alpes.fr`

Abstract. The evolution of disk hosting young stellar objects over the time frame 1-10 Myr is briefly reviewed. Emphasis is put on mass accretion rate and stellar magnetic field, two central ingredients that dictate the nature of the star-disk interaction. The magnetospheric accretion process appears to be responsible for a large part of the short-term spectrophotometric variability of young stellar objects, one of their defining properties indeed.

Key words. Stars: pre-main sequence – Stars: accretion - Stars: magnetic field

1. Introduction

Over the 1-10 Myr time frame, young solar-type stars accrete material from their circumstellar disk. Accretion of material from the inner disk edge to the central star is a complex and dynamical process that still remains to be fully elucidated (see, e.g., Romanova & Owocki, 2015).

Magnetically controlled accretion streams play a central role in defining the spectrophotometric properties of young stellar objects (YSOs), e.g., their X-ray and UV excesses, and rich emission-line spectrum. Magnetospheric accretion is also responsible for most of the variability YSOs exhibit on day to week timescales.

I review here some recent results related to the star-disk interaction and YSOs variability, namely accretion disk lifetimes, mass accretion rate, and stellar magnetic field evolution at the time of planetary formation.

2. Disk lifetimes

Most solar-type stars are born with disks which dissipate on a timescale of a few Myr, possibly through the combined action of accretion processes and photoevaporative outflows (e.g., Alexander et al., 2014). Spectacular images of circumstellar disks around embedded stellar objects at an age less than 1 Myr have recently been released by ALMA (e.g. HL Tau, ESO PR No. 1436). Significantly older T Tauri stars, such as TW Hya at an age 8 Myr, may also exhibit such large-scale disks (Andrews et al., 2016). Most population studies indicate *a steady decrease of disk hosting stars* in young stellar associations over the time frame from 1 to 10 Myr (e.g., Fedele et al., 2010; Bell et al., 2013), with initial and environmental conditions possibly impacting disk lifetimes locally (e.g., Rosotti et al., 2014; Daemgen et al., 2016). While it is quite clear that the disk lifetime varies from star to star, even within the same stellar group, *the average primordial disk lifetime appear to lie within 3-6 Myr*, depending on age estimates assigned to star forming regions (e.g., Meng et al., 2017), with reports of strong accretors up to late ages (e.g., Ingleby et al., 2014). How the average disk lifetime varies with stellar mass remains controversial, with contrasting observational results (e.g., Ribas et al., 2015; Galli et al., 2015; Liu et al., 2015). A relationship has been suggested between accretion disk lifetime and initial stellar angular momentum content, which might find its origin in the embedded protostellar phase (Gallet & Bouvier, 2013). Overall, even though the relative timescales for gas and dust evolution in protoplanetary disks still have to be refined, the accretion process appears to last over about the same duration as planet formation in the disk, and may thus have important consequences for the early evolution of planetary systems.

3. Mass accretion rate

Mass accretion rates have now been measured for hundreds of YSOs in various star forming regions, most often by converting emission line fluxes to accretion rates using empirical calibrations (e.g., Frasca et al., 2015; Manara et al., 2015), and sometimes from directly measuring and modeling the UV excess arising from the accretion shock at the stellar surface (e.g., Rigliaco et al., 2012; Alcalá et al., 2014). Empirical relationships have been derived between the mass accretion rate and the mass of the central star, $\dot{M}_{acc} \propto M_\star^\alpha$, with $\alpha \sim$ 1.4-2.1 for subsolar mass stars, an exponent that becomes possibly steeper for very low mass stars and brown dwarfs, and shallower for intermediate-mass stars (e.g., Venuti et al., 2014; Manara et al., 2016; Alcalá et al., 2017). *Typical mass accretion rates in the (sub)solar-mass range lie between* $\dot{M}_{acc} \sim 10^{-9}$ *and* 10^{-7} $M_\odot yr^{-1}$*, with a scatter of about a factor 100 at any given mass* (see Figure 1). This scatter is well in excess of the typical accretion variability amplitude of 0.5 dex (Costigan et al., 2014; Venuti et al., 2015), and may result from an age dispersion in young stellar populations, from different accretion regimes onto the central star, or may reflect the impact of initial /environmental conditions –see the discussion in Venuti et al. (2014). The time dependence of mass accretion rate is not as confidently documented from observations, due to the difficulty to assign precise ages to individual stars in young stellar groups. Indeed, we are still missing a robust statistical investigation of the decline of the average mass accretion rate from one star forming region to the next over the time frame 1-10 Myr, similar to what has been done for the evolution of the disk fraction. Monte Carlo simulations of angular momentum evolution that assume a time-dependent mass accretion rate $\dot{M}_{acc} \propto t^{-1.5}$, as predicted by viscous disk evolution (Hartmann et al., 1998), nevertheless appear to recover most of the empirical rotation-accretion relationships reported for young stars (Vasconcelos & Bouvier, 2015).

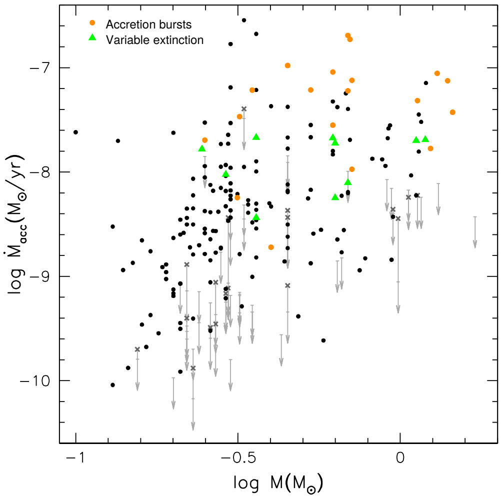

Fig. 1. The $\dot{M}_{acc}$ distribution of low mass YSOs in the 5 Myr-old star forming region NGC 2264 is plotted as a function of stellar mass. Vertical arrows indicate upper detection limits. Orange dots and green triangles mark two subgroups of objects whose photometric variability is dominated by stochastic accretion bursts and variable circumstellar extinction, respectively. Figure from Venuti et al. (2014).

4. Magnetic field

The determination of the magnetic properties of young stars has known a spectacular development over the last decade. The intensity and topology of the large-scale magnetic field structure have now been measured for a significant sample of accreting T Tauri stars (e.g., Donati et al., 2011, 2012, 2013; Johns-Krull et al., 2013) and Herbig Ae-Be stars (e.g., Alecian et al., 2013). *Young solar-type stars exhibit large-scale fields with an intensity in the range from a few hundred to a few thousand Gauss, and a geometry that is usually a mix of dipolar and octupolar components,* with a ratio that appears to depend on evolutionary status (Gregory et al., 2012). Such strong magnetospheres have a direct impact on the inner accretion disk: the magnetic pressure is strong enough to overcome the gas pressure in the inner disk up to a distance of a few stellar radii above the photosphere, thus effectively truncating the inner disk region at a distance of typically 0.03-0.08 AU (e.g., Johnstone et al., 2014). The accretion flow from the inner disk to the stellar surface then proceeds along magnetic funnel flows, a process often referred to as *magnetospheric accretion* (for a review, see, e.g., Bouvier et al., 2007b). The dynamo-generated magnetic field rapidly decreases as the stars reach the ZAMS and evolve further on the main sequence (Vidotto et al., 2014; Folsom et al., 2016). This is illustrated in Fig. 2 where the intensity of the mean large scale magnetic field of solar-type stars is plotted as a function of age, from the early pre-main sequence up to the solar age. On the basis of an extended sample of solar-type stars at various evolutionary stages, Folsom et al. (2016) argued that the weakening of the magnetic field strength during the pre-main sequence primarily results from structural changes, while it closely follows the rotational braking of solar-type stars on the main sequence.

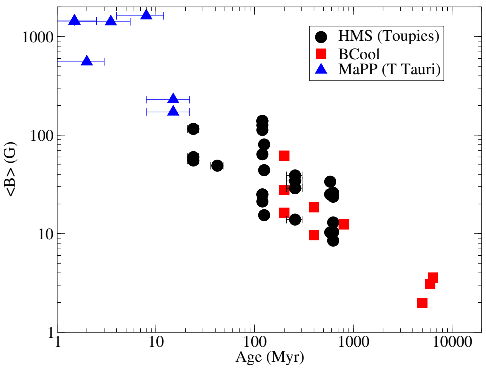

Fig. 2. The mean large-scale magnetic field strength of solar-type stars is plotted as a function of age from the early pre-main sequence to the age of the Sun. Magnetic field measurements were obtained in the framework of 3 major spectropolarimetric surveys (shown as different symbols) targeting T Tauri stars (MAPP; Donati et al. 2013), zero-age main sequence stars (HMS/Toupies; Folsom et al. 2016), and late-type dwarfs (Bcool; Marsden et al. 2014). Figure updated from Folsom et al. (2016).

5. Star-disk interaction and photometric variability

The evolution of mass accretion rate and magnetic field strength and topology over the 1-10 Myr age range is a major factor impacting star-disk interaction and angular momentum evolution (see, e.g., Bouvier et al., 2014). Strong large-scale dipolar fields, as observed in fully convective PMS stars on their Hayashi tracks (e.g., Donati et al., 2013), are most effective in truncating the inner disk and channeling the accretion flow along the stellar magnetosphere down to the stellar surface, where it produces a localized accretion shock. The tilted magnetic configuration gives rise to an inner disk warp that periodically obscures the central star, to funnel flows of ionized gas where part of the emission line spectrum of accreting T Tauri stars originates, and to the rotational modulation of the continuum excess flux, including optical veiling and soft X-ray excess, produced in the accretion shock located close to the magnetic pole. These signatures are predicted by numerical models of MHD star-disk interaction (e.g., Romanova et al., 2012; Matsakos et al., 2013; Orlando et al., 2013), they were observed in the prototypical case of AA Tau (Bouvier et al., 2003, 2007a; Grosso et al., 2007), and are now commonly reported for accreting YSOs (Alencar et al., 2010; Flaccomio et al., 2010; Fonseca et al., 2014; McGinnis et al., 2015; Sousa et al., 2016). These so-called photometric dippers (Cody et al., 2014a; Stauffer et al., 2015) whose light curve is dominated by ex-

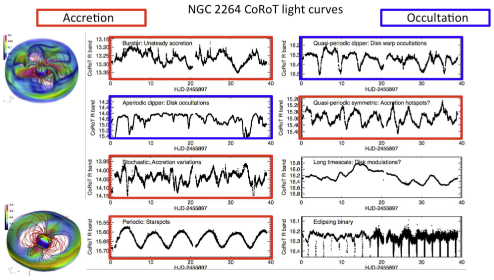

Fig. 3. A few examples of CoRoT light curves obtained for YSOs in NGC 2264 during the CSI2264 campaign. Adapted from Cody et al. (2014b) with illustrations of star-disk MHD simulations from Kurosawa & Romanova (2013).

tinction events are characterized by relatively mild accretion rates, as shown in Figure 1. In contrast, the strongest accretors often exhibit stochastic light-curves, sometimes including short duration accretion bursts (Stauffer et al., 2014, 2016), suggesting a much more dynamical and unstable accretion flow onto the star, as expected from numerical star-disk interaction models (Kurosawa & Romanova, 2013). Some examples of the light curves obtained during the most ambitious photometric space campaign dedicated to YSOs, dubbed CSI 2264 (Coordinated Synoptic Investigation of NGC 2264; Cody et al., 2014a) are shown in Figure 3. Some of these light curves appear to be dominated by non-steady accretion events onto the star, on timescales ranging from hours to weeks, while others exhibit evidence for obscuration by orbiting circumstellar dust. Even though much of the photometric variability of YSOs on day to week timescales remains to be understood, *the recent progress brought by space photometry seems to support the existence of at least two main regimes of star-disk interaction, namely stable and unstable, which are partly reflected in the optical light curves* (e.g., Siwak et al., 2016). The monitoring of hundreds of YSOs in other star forming regions with K2 will undoubtedly bring additional insight into the processes at the origin of one of the defining properties of YSOs, namely their ubiquitous variability on timescales ranging from hours to years.

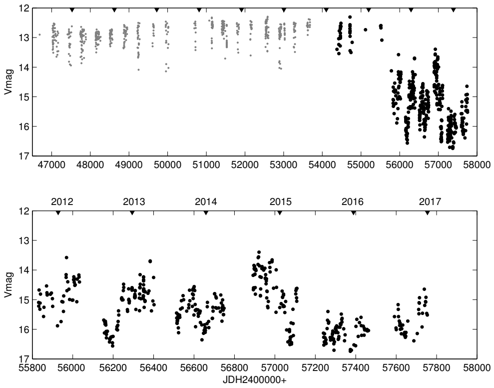

Fig. 4. Updated AA Tau V-band light curve (K. Grankin, priv. comm.). *Upper panel:* A 30-year long light curve of AA Tau, from 1987 to 2017. *Lower panel:* Part of AA Tau's light curve from 2011 to 2017, highlighting the epoch of the on going dimming.

6. Long-term variability: Eruptive vs. dimming YSOs

Two main classes of eruptive YSOs have been known for long: FUors and EXors (see., e.g., S. Stahler, this volume). The former exhibit a sudden brightening of several magnitudes on a month timescale followed by decades of slow fading, while the latter are characterized by repetitive, shorter timescales outbursts, with an amplitude of a few magnitudes (see Audard et al., 2014, for a recent review). Both classes of eruptive objects are thought to experience massive episodic accretion events that are triggered by large-scale instabilities in the circumstellar disk. Interestingly, wide-field infrared photometric surveys have recently revealed a continuum of outburst timescales and amplitudes, intermediate between FUors and EXors, which suggest that episodic accretion may be a relatively common process over the lifetime of circumstellar disks, with a frequency occurrence that decreases from the embedded phase to the T Tauri stage (e.g., Contreras Peña et al., 2017). *Indeed, the photometric behavior of T Tauri stars is hardly predictable on the long-term.* Spectacular examples of unexpected sudden fading of sources considered as "well-behaved", i.e., that have shown the same type of variability over several decades (Grankin et al., 2007), have recently been reported, including AA Tau itself (Bouvier et al., 2013) –see its updated light curve in Figure 4, and RW Aur (Rodriguez et al., 2013). Large dimming events, with an amplitude of several magnitudes and lasting for months to years, may prove to be much more common in T Tauri stars than previously thought (see, e.g., Rodriguez et al., 2017). How do these large scale dimming events possibly relate to eruptive accretion episodes and/or planet formation in the disk remains to be explored.

7. Conclusion

The concomitant evolution of accretion rate and magnetic field over the time frame 1-10 Myr in the early life of solar-type stars strongly influences their fate. Not only do these changes instantaneously impact the accretion-ejection process, and in particular the physics of the star-disk interaction, but they also have long lasting consequences for angular momentum evolution, internal stellar structure, and possibly planet formation and evolution. A better understanding of the physical processes at work during this short but important evolutionary phase has been gained over the last years, thanks in part to dedicated campaigns and large programs aimed at characterizing the magnetic, photometric, and spectroscopic properties of large samples of YSOs in various star forming regions. These recent results have spectacularly broadened the variety of phenomena and behaviors observed to occur in YSOs, thus opening a new chapter in the study of these intriguing objects.

Acknowledgements. I thank the organizers of this conference; it has been a pleasure to have the opportunity to honor Francesco's memory. I am indebted to Laura Venuti, Colin Folsom, and Konstantin Grankin, who provided Figures 1, 2, and 4 of this contribution, respectively, and to Ann Marie Cody who allowed the use of Figure 3.

References

Alcalá, J. M., Natta, A., Manara, C. F., et al. 2014, A&A, 561, A2
Alcalá, J. M., Manara, C. F., Natta, A., et al. 2017, A&A, 600, A20
Alecian, E., Wade, G. A., Catala, C., et al. 2013, MNRAS, 429, 1001
Alencar, S. H. P., Teixeira, P. S., Guimarães, M. M., et al. 2010, A&A, 519, A88
Alexander, R., et al. 2014, in Protostars and Planets VI, H. Beuther et al. eds. (Univ. Arizona Press, Tucson), 475
Andrews, S. M., Wilner, D. J., Zhu, Z., et al. 2016, ApJ, 820, L40
Audard, M., Ábrahám, P., Dunham, M. M., et al. 2014, in Protostars and Planets VI, H. Beuther et al. eds. (Univ. Arizona Press, Tucson), 387
Bell, C. P. M., et al. 2013, MNRAS, 434, 806
Bouvier, J., Grankin, K. N., Alencar, S. H. P., et al. 2003, A&A, 409, 169
Bouvier, J., Alencar, S. H. P., Boutelier, T., et al. 2007a, A&A, 463, 1017
Bouvier, J., Alencar, S. H. P., Harries, T. J., Johns-Krull, C. M., & Romanova, M. M. 2007b, in Protostars and Planets V, B. Reipurth et al. eds. (Univ. Arizona Press, Tucson), 479
Bouvier, J., et al. 2013, A&A, 557, A77
Bouvier, J., Matt, S. P., Mohanty, S., et al. 2014, in Protostars and Planets VI, H. Beuther et al. eds. (Univ. Arizona Press, Tucson), 433
Cody, A. M., Stauffer, J., Baglin, A., et al. 2014a, AJ, 147, 82
Cody, A. M., Stauffer, J., & Bouvier, J. 2014b, European Physical Journal Web of Conferences, 64, 08004
Contreras Peña, C., Lucas, P. W., Minniti, D., et al. 2017, MNRAS, 465, 3011
Costigan, G., et al. 2014, MNRAS, 440, 3444
Daemgen, S., et al. 2016, A&A, 586, A12
Donati, J.-F., Gregory, S. G., Alencar, S. H. P., et al. 2011, MNRAS, 417, 472
Donati, J.-F., Gregory, S. G., Alencar, S. H. P., et al. 2012, MNRAS, 425, 2948
Donati, J.-F., Gregory, S. G., Alencar, S. H. P., et al. 2013, MNRAS, 436, 881
Fedele, D., et al. 2010, A&A, 510, A72
Flaccomio, E., et al. 2010, A&A, 516, L8
Folsom, C. P., Petit, P., Bouvier, J., et al. 2016, MNRAS, 457, 580
Fonseca, N. N. J., et al. 2014, A&A, 567, A39

Frasca, A., Biazzo, K., Lanzafame, A. C., et al. 2015, A&A, 575, A4
Gallet, F. & Bouvier, J. 2013, A&A, 556, A36
Galli, P. A. B., et al. 2015, A&A, 580, A26
Grankin, K. N., et al. 2007, A&A, 461, 183
Gregory, S. G., Donati, J.-F., Morin, J., et al. 2012, ApJ, 755, 97
Grosso, N., Bouvier, J., Montmerle, T., et al. 2007, A&A, 475, 607
Hartmann, L., et al. 1998, ApJ, 495, 385
Ingleby, L., Calvet, N., Hernández, J., et al. 2014, ApJ, 790, 47
Johns-Krull, C. M., Chen, W., Valenti, J. A., et al. 2013, ApJ, 765, 11
Johnstone, C. P., et al. 2014, MNRAS, 437, 3202
Kurosawa, R. & Romanova, M. M. 2013, MNRAS, 431, 2673
Liu, Y., et al. 2015, A&A, 582, A22
Manara, C. F., et al. 2015, A&A, 579, A66
Manara, C. F., et al. 2016, A&A, 585, A136
Marsden, S. C., Petit, P., Jeffers, S. V., et al. 2014, MNRAS, 444, 3517
Matsakos, T., Chièze, J.-P., Stehlé, C., et al. 2013, A&A, 557, A69
McGinnis, P. T., Alencar, S. H. P., Guimarães, M. M., et al. 2015, A&A, 577, A11
Meng, H. Y. A., et al. 2017, ApJ, 836, 34
Orlando, S., Bonito, R., Argiroffi, C., et al. 2013, A&A, 559, A127
Ribas, Á., Bouy, H., & Merín, B. 2015, A&A, 576, A52
Rigliaco, E., Natta, A., Testi, L., et al. 2012, A&A, 548, A56
Rodriguez, J. E., Pepper, J., Stassun, K. G., et al. 2013, AJ, 146, 112
Rodriguez, J. E., Zhou, G., Cargile, P. A., et al. 2017, ApJ, 836, 209
Romanova, M. M., et al. 2012, MNRAS, 421, 63
Romanova, M. M. & Owocki, S. P. 2015, Space Sci. Rev., 191, 339
Rosotti, G. P., Dale, J. E., de Juan Ovelar, M., et al. 2014, MNRAS, 441, 2094
Siwak, M., Ogloza, W., Rucinski, S. M., et al. 2016, MNRAS, 456, 3972
Sousa, A. P., Alencar, S. H. P., Bouvier, J., et al. 2016, A&A, 586, A47
Stauffer, J., Cody, A. M., Baglin, A., et al. 2014, AJ, 147, 83
Stauffer, J., Cody, A. M., McGinnis, P., et al. 2015, AJ, 149, 130
Stauffer, J., Cody, A. M., Rebull, L., et al. 2016, AJ, 151, 60
Vasconcelos, M. J. & Bouvier, J. 2015, A&A, 578, A89
Venuti, L., Bouvier, J., Flaccomio, E., et al. 2014, A&A, 570, A82
Venuti, L., Bouvier, J., Irwin, J., et al. 2015, A&A, 581, A66
Vidotto, A. A., Gregory, S. G., Jardine, M., et al. 2014, MNRAS, 441, 2361