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P. Di Matteo, O. Creevey, A. Crida, G. Kordopatis, J. Malzac, J.-B. Marquette, M. N'Diaye, O. Venot (eds)

YOUNG STARS AS SOURCES OF ENERGETIC PARTICLES

A. Marcowith[1]

Abstract. This short review discusses the possible role of energetic particles (EP) in the physics and the evolution of young stellar objects (YSO). It also shortly addresses the interest of EP production in M-dwarf stars and their impact over their planetary system. It is advocated here that the role EPs in such systems needs to be properly evaluated in the light of a series of new observations which support the possibility of an in-situ production of high fluxes of EP.

Keywords: Young Stellar Objects - Energetic particles - Acceleration mechanisms - Cosmic Rays.

1 Introduction

Young stellar objects (YSO) share some similarities with compact objects: both have an accretion disk dragging external matter towards the central object under the effect of gravitation and magnetic fields, both show ejection in the form of outflows or jets that originate either from the central object itself or from the disk. YSOs are very active objects (Feigelson & Montmerle 1999); they show a strong X-ray activity which likely originates from the interaction between the stellar magnetosphere and the accretion disk (but not only). YSO are important objects for different active scientific contexts. First, YSO contribute to the feed-back process in the star formation cycle as a strong source of radiation and kinetic energy via their jets which impact the surrounding interstellar medium (Nakamura & Li 2007; Offner & Chaban 2017). Secondly, YSO at the end of their formation stage are the birth place of planets through the formation of proto-planetary disks (Armitage 2011). In at least these two contexts the possible impact of energetic particles (EP), ie particles with kinetic energies above the typical temperature of the medium, hence which can be renamed as non-thermal, have been largely overlooked until recently.

Besides these considerations, we are now entering in an unprecedented precision era in the study of the solar corona activities as we expect soon the first data from the Solar Parker probe [*]. We know that the Sun is a source energetic particles (Klein & Dalla 2017), and was also more active in the past (Feigelson & Montmerle 1999). It is highly tempting then to see YSO as test-bed objects at the intersection of solar and space plasma physics and high-energy Astrophysics communities interests. Theoretical models of particle acceleration developed in these fields may be used to investigate the loosely known effect of EP over their dynamics. This is the main motivation of this short review. On the specific aspect of the study of particle acceleration, YSO are also interesting objects because –as we will see below– the maximum energies reached by in-situ accelerated EPs are more modest (but still relativistic) with respect to typical usual Cosmic Ray (CR) sources (Supernova remnants, pulsar wind nebula), hence the study of particle acceleration in these objects necessitates less dynamics in space, time (and energy) and are more accessible to modern numerical tools specifically developed for this subject. This aspect should motivate theorists to consider YSO as promising test beds for particle acceleration studies in the view to evaluate the potential impact of EPs on star and planet formation.

The outlines of the article are as follows. After this short introduction, section 2 presents some recent evidences of the presence of energetic particles in YSO, we will then argue with simple energetic arguments that these EP are in-situ produced and not background CRs; these are unable to propagate close to the star. In section 3 we give an overview of the different acceleration mechanisms and EP production sites in YSO. This section also shortly discusses the case of EP in active M-dwarfs. In section 4 we focus on some recent work done in solar-mass and high-mass YSO on the possibility to accelerate particle by first order Fermi acceleration at shocks. Section 5 lists different issues associated with particle acceleration models and suggests some research directions before our final conclusion in section 6.

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[1] Laboratoire Univers et Particules de Montpellier, UMR 5299 du CNRS, Université de Montpellier, place E. Bataillon, cc072, 34095 Montpellier, France

[*] http://parkersolarprobe.jhuapl.edu/

2 Observational evidences of non-thermal particles in young stellar objects

2.1 Schematic view of YSO

YSO are multi-scale physics objects. At scales of 0.1-1 pc they show outflows and jets harboring complex substructures composed of knots and hot spots (Bally 2016). At scales of 0.1-100 AU a central magnetized star in rotation accretes matter from an outer enveloppe of gas. The bipolar outflows and jets are launched from the disk or from the star magnetosphere (or from the interaction zone between the two). Low and intermediate mass (with masses between 0.2-2 $M_\odot$) YSOs belong to class 0, I, II, III depending on their evolution stage before entering in the main sequence phase (Feigelson & Montmerle 1999). The T Tauri phase which covers classes II and III typically lasts for 1-10 Myrs.

2.2 Magnetic activity in M-dwarfs

M-dwarfs are low mass stars with masses 0.1-0.5 $M_\odot$, with low surface temperatures and luminosities $\sim 0.01 L_\odot$. They have surface magnetic fields reconstructed by Zeeman Doppler imaging techniques in the range of 100-1000 Gauss (Vidotto et al. 2013). As for these stars the so-called habitable zone is typically of the order of 0.1 AU, their strong magnetic activity can then have a direct impact over the orbiting planets in this zone (Lammer et al. 2007).

2.3 Energetic particles in YSO: observations

EP can back-react over the structures in YSO through different mechanisms. MeV protons and keV electrons can ionize and produce a heating of the surrounding matter at high density columns where either U.V. or X-ray radiation can not penetrate (Padovani et al. 2018b). These EP can also trigger molecular Hydrogen dissociation (Padovani et al. 2018a). Particles produced by radioactive decay can also contribute to a minimum ionization rate (Cleeves et al. 2013). MeV-GeV hadrons can interact with the local matter and induce spallative nucleosynthesis (Padovani et al. 2016). Relativistic electrons can produce radio synchrotron emission and then trace the local magnetic field amplitude and topology (the synchrotron radiation is polarized), see eg Rodríguez-Kamenetzky et al. (2016). Finally, high energy protons/electrons can also produce gamma-rays via different processes: Bremsstrahlung and Inverse Compton (for electrons) and pion decay (for protons), see eg Bosch-Ramon et al. (2010). Gamma-ray emission if detected can put constraints on the magnetic field amplitude, or/and background photon and matter densities. Gamma-ray emission through the kinetic energy imparted into EP can also help to constrain source energetics.

Let us now discuss some recent observations which probe the presence of EP in YSO. We will then argue that these EP are necessarily in-situ produced.

Ionization rates Ceccarelli et al. (2014) present Herschel-HIFI observations of the young protostar, OMC-2 FIR 4 with enhanced abundances of two molecular ion species HCO^+ and N_2H^+ in the envelope of the object. These abundances are compatible with ionization rates up to 3-5 orders of magnitude above the standard Sptizer value of $\xi = 3\ 10^{-17}\mathrm{s}^{-1}$. The flux of EP extrapolated at a distance of 1 AU from the emitting source can easily account for the irradiation required by meteoritic observations (see below). Since then, several observations have confirmed these results and also show the presence of non-thermal radio emission (Favre et al. 2017; Fontani et al. 2017). Still using Herschel observations Podio et al. (2014) obtained enhanced ionization rates in the hotspot region of the low mass YSO LH1157-B1.

These ionization rates are difficult to explain only invoking the effect of background (ISM) CR. Indeed, the gravitational luminosity of accretion shocks impinging the stellar surface at a radius $R_{\rm sh} = 0.02$ AU is $L_{\rm grav} = GM\dot{M}/R_{\rm sh} \sim 3\ 10^{34}$ erg/s for a class 0 YSO with 0 protostar with $M = 0.1 M_\odot$, $\dot{M} = 10^{-5} M_\odot$yr. The background (ISM) CR luminosity impinging the core of a molecular cloud of radius $R_{\rm core} = 0.1$ pc is $L_{\rm CR} \simeq R_{\rm core} V_{\rm a} e_{\rm CR} \sim 10^{29}$ erg/s, for a typical Alfvén speed $V_{\rm a} = 1$ km/s and a CR energy density $e_{\rm CR} \simeq 1$ ev/cm^3 (Padovani et al. 2016). Now the CR luminosity close to the star is strongly reduced due to strong ionization losses and/or modulation, hence a small fraction of $L_{\rm grav}$ injected into in-situ accelerated EP can easily dominates $L_{\rm CR}$. A conclusion also true in high mass YSO since $\dot{M}$ can be higher.

Meteoritic measurements Carbonaceous chondrules are conglomerates of melted rock (chondrules), rare melted Ca-Al rich inclusions (CAIs) and presolar (interstellar) carbonaceous grains. They have been flashmelted to temperatures ∼2000 K. Polarization analysis show they have been formed in the presence of Gauss-level magnetic fields 4.55 Gyr ago (Feigelson & Montmerle 1999). Radioactive nuclei (for instance ^{10}Be, with a half-time live of $t_{1/2} \sim 1.4$ Myr) have been detected in CAIs is such abundance that they require the young solar system to have been plunged in an intense flux of EP (Jacquet 2019). The origin of this flux is still debated: it is either associated with the activity of massive stars in the environment of the young Sun (Tatischeff et al. 2014) or due to solar flare particles (Gounelle et al. 2013).

Flaring activity YSO show intense X-ray activity in form of flares with keV luminosities $L_{\rm X} \sim 10^{33-35}$ erg/s (Feigelson et al. 2002) consistent with magnetic power released during intense reconnection events (see below). In fact the energy released in X-ray domain is a small fraction of the total flare energy (Emslie et al. 2012). The typical flare duration last from 0.5 to 12 hr, the flares are $10^{2.5}$ more frequent with respect to Solar flares and $10^{1.5}$ more luminous. This supports an expected EP fluence 5 orders of magnitude larger than the one produced by the present Sun (Feigelson et al. 2002). Longer term observations (over 13 days) by Chandra allow the analysis of the flare decay profile. The profile and the duration of the flares point toward a spatial extension of the stellar corona- inner disk region $L/R_\star$ larger than 5-10 (Favata et al. 2005). Getman et al. (2008) scan X-ray flares from a sample of disk-free and accreting stars, the authors find flaring regions which are large and in corotation. Class II & III YSO also show non-thermal variable radio emission (Andre 1996).

Synchrotron emission from jets Several recent observations have reported negative (lower than -0.3) index non-thermal radio emission at cm wavelengths in several YSO (Anglada et al. 2018; Purser et al. 2016; Rodríguez-Kamenetzky et al. 2016). In particular (Rodríguez-Kamenetzky et al. 2017) propose unprecedented precise observations of HH80 and HH81 using the JVLA facility. These observations show a modulation of the cm radio index with the jet geometry: positive indexes correspond to the regions where the jet gets narrow while negative indexes correlate with a widening. This may be interpreted as a result of recollimation shocks in the jet pattern.

3 Acceleration sites and acceleration mechanisms

3.1 Acceleration sites

Jets YSO produce complex jet structures composed of outflows with speed of a few tens km/s and internal spines moving at higher speed from a few hundred km/s in low mass YSO up to 1000 km/s or more in high mass YSO. In these jets transitory structures appear as knots or spots that may be due to recollimation shock waves or may be associated with an unstable ejection mechanism (Raga et al. 2002). The fast jet are expected to end as a hot spot composed of an external bow shock and an internal shock (Bosch-Ramon et al. 2010). One of major limiting factor for particle acceleration at fast shock in jets is the level of ionization of the upstream medium (Padovani et al. 2016). Neutrals indeed through their collisions with ions produce some damping of ion motions and thus of waves supporting the scattering of EPs. Another unknown is the magnetic field strength in the jet which controls the confinement of particles around the shock. Finally, probably the most important unknown is the fraction of shock kinetic energy imparted into EP (see section 4 for some estimates).

Accretion disk corona Accretion disks around YSO are composed of multi-layered materials. The outer part of the accretion disk have smaller density column and are more prone to be ionized. Another aspect, is that the magnetic field carried with the accreted material can have some turbulent component or be subject to some instability (buoyancy, magneto-rotational instability, ...) which can eventually reconnect during the rotation motion around the central object. Also here the main unknown is the fraction of magnetic energy which can be transferred to EPs. The magnetic energy is also transfer into heat that participes to the production of some transitory coronas, there the magnetic energy can also be dissipated into some turbulence which can produce stochastic Fermi acceleration (see below) as it has been argued in the context of compact objects (Dermer et al. 1996).

Magnetosphere-disk interaction zone As stated above, the zone of interaction between the stellar magnetosphere and the accretion is known to be active, an activity also likely connected with magnetic reconnection. These events can lead to particle acceleration (de Gouveia Dal Pino et al. 2010; del Valle et al. 2011). Some non-thermal radio emission has been detected during intense X-ray activity which can marks such an acceleration process (see above). The stellar magnetic field can also channel accreted matter towards the stellar surface which end as accretion shocks (Feigelson & Montmerle 1999).

Stellar energetic particles Of course, as young stars are active stars they can be sources of stellar energetic particles accelerated during magnetic reconnection in the stellar corona or produced at shocks associated with coronal mass ejections events as it is the case for our Sun. This process is of particular relevance in M-dwarfs (Tabataba-Vakili et al. 2016).

3.2 Acceleration mechanisms

These mechanisms are (rather) well known. My intent here is to discuss some specific aspects of these processes in the environment of YSOs.

First order Fermi acceleration at shocks Fermi regular or first order acceleration is produced because shock waves carry the scattering waves and then impose a bulk motion. At each shock crossing then particles start to interact via head-on collisions and then have a systematic gain in energy. On average (over a Fermi cycle, eg up-down-up stream) EP gain $\langle \Delta E/E \rangle \propto (v/U)$. This process is of particular interest because beside being more efficient it also produces solutions in form of power-laws which only depend on one parameter, ie the shock compression ratio (at least in the linear stage).
The typical energy density available for EPs in these environment can be scaled as $E_{\rm kin} \simeq 10^3 \ \mu n_{\rm H,5} V_{\rm sh,1}^2$ eV/cm^3, where μ is the mean gas mass, $n_{\rm H,5}$ is the hydrogen density in units of 10^5 cm^{-3}, and $V_{\rm sh,1}$ is the shock speed in units of km/s. Unless a fraction less than 10^{-3}% of this energy is converted into EP, the energy density imparted in these particles is higher than the background CR local energy density. The total power released into EP can be evaluated by estimating a ratio of the volume V over which particles are injected divided by a typical time T which can be at most the dynamical time of the shock, then $E_{\rm kin} \sim 7 \ 10^{23} \ \mu n_{\rm H,5} V_{\rm sh,1}^2 V_{\rm AU}/T_{\rm yr}$ erg/s, where we have estimated the volume $V_{\rm AU}$ in units of AU^3 and the time in year units. Using the above example of a class 0 object we find $E_{\rm kin} \sim 2 \ 10^{26} \ \mu n_{\rm H,12} V_{\rm sh,250}^2$ erg/s, the shock speed is now in units of 250 km/s and the Hydrogen density in units of 10^{12} cm^{-3}, hence a typical power of 10^{24} erg/s can be imparted into EPs (Padovani et al. 2016), still much higher than the power in background CR propagated into high density columns (more than 10^{25} cm^{-2}). For jets, one may expect roughly $E_{\rm kin} \sim 10^{33} \ \mu n_{\rm H,5} V_{\rm sh,100} \ R_{\rm perp,100}^2$erg/s, so about 10^{31} erg/s in EPs, making shock acceleration a probable acceleration mechanism (see section 4). Here we use as jet cylindical radius $R_\perp = 100$ AU.

Magnetic reconnection There is not a unique way to accelerate particles in magnetic reconnection (REC), ie the process by which the topology of magnetic field lines get rearranged and are converted into magnetic energy, heat, plasma bulk motion and EPs. Actually, there are at least 7 ways particles can gain kinetic energy is such events: in thermal exhausts, in contracting plasmoid, in colliding plasmoid, by the reconnecting electric field, by Fermi first order acceleration in converging reconnection flows, by magnetic drifts, by turbulence generated by for instance the tearing instability appearing during the reconnection process.
Here the available energy density is stored in the magnetic field. Typical values in the disk are $E_{\rm B} \sim 2.5 \ 10^{10} \ B_{\rm G}^2$eV/cm^3, where the magnetic field strength is in Gauss units. It is easy to understand why, at least locally, especially close to the star where kG field strengths are found, REC can be an important source of EP. In solar reconnection events gamma-ray observations show that a significant fraction (up to 50%) of the magnetic energy released in the events can be converted into EP (Krucker et al. 2010). A rough estimate by del Valle et al. (2011) for conditions that prevail in the magnetosphere of a T Tauri star gives about a power of 10^{32} erg/s injected into EP per event. Compared to the above estimate this process may dominate over Fermi first order acceleration in the stellar magnetosphere but less likely in jets as the magnetic field strength is expected to drop along the jet (however a clear answer necessitates to evaluate the reconnection area, and the variation of the Alfvén speed).

Stochastic Fermi acceleration Stochastic Fermi acceleration (SFA) occurs because, on average EPs at a speed v interact with scattering centers moving at a speed U more often through head-on collisions than through rear-on collisions because $v \gg U$. At each head-on interaction EPs have a relative energy boost while they are decelerate in rear-on collisions. The averaged relative energy gain is $\langle \Delta E/E \rangle \propto (v/U)^2$. Usually in Astrophysics

U is close to the local Alfvén speed which is the typical speed of MHD waves (unless the plasma parameter is much larger than one). SFA is especially interesting if the magnetic field amplitude is high and the plasma density is low enough for U to be close to the speed of light and/or for moderately relativistic particles.
Here the value of available energy density is rather uncertain because it requires to know what fraction of primary source of energy (gravitation, kinetic or magnetic) goes into turbulent motions and what fraction of it goes into magnetic turbulent fluctuations. Actually there are no consensus on the main instability at the origin of turbulent motions in either accretion disks or jets, so any derivation of the turbulent energy density seems premature (see however some estimates in the context of black hole accretion flows in Dermer et al. (1996)).

4 Shock acceleration in YSO

We now focus a bit more on one mechanism in particular: the Fermi first order shock acceleration in YSO jets.

4.1 Modeling low-mass YSO

Ionization rates obtained in section 2.3 are difficult to explain unless invoking an in-situ source of EP. Padovani et al. (2016) consider the possibility to accelerate EP at shocks propagating in the jet of low mass YSO. The main parameters of the model necessary for the calculation of the acceleration time are: the shock speed $V_{\rm sh}$ in the range 40-300 km/s, the upstream (jet) temperature $T_{\rm u}$ in the range $10^4 - 10^5$ K, the jet Hydrogen density $n_{\rm H}$ in the range $10^3 - 10^7$ cm^{-3}, the jet magnetic field strength $B_{\rm u}$ in the range $0.05 - 1$ mG and an ionization fraction X in the range 0.01-0.9.
To derive the flux of in-situ accelerated CR one need a last parameter which is the fraction ξ of the shock ram pressure $n_{\rm H} m_{\rm p} V_{\rm sh}^2$ imparted into EP: $m_{\rm p}$ is the proton mass. This parameter is one of the main unknown in shock acceleration theories and is usually adjusted using observations. In this work Padovani et al. (2016) consider ξ of the order of a few %. Maximum EP energies are obtained by comparing the acceleration timescale $t_{\rm acc} \propto \kappa_{\rm u}/V_{\rm sh}^2$ to a series of loss times. In a jet different loss effects can occur: transversal diffusive escape, escape by advection downstream, escape by diffusion upstream, radiative losses (ionization losses at low energies), escape due to wave damping by ion-neutral collision. A last modeling effort is needed to characterize $\kappa_{\rm u}$ the diffusion coefficient of EPs in the upstream medium. This one is parametrized with respect to its Bohm value; ie $\kappa_{\rm u} = k_{\rm u} r_{\rm L} v/3$, where $r_{\rm L}$ and v are the EP gyroradius and speed respectively and $k_{\rm u}$ is a constant.
Padovani et al. (2016) find that shock in jets of low mass YSO under these conditions are able to accelerate EP up to energies of a few tens of GeV. Particle distribution follow power-laws with an energy index close (but larger) to 2. Fluxes are able to explain, accounting for the uncertainty in the propagation of the particles between the shock and the interaction zone, the high ionization rates observed in OMC-FIR4 [†]and LH1157-B1 and also to explain the radio emission of one hot spot of DG Tau (Ainsworth et al. 2014).

4.2 Modeling high-mass YSO

In high mass YSO, shock speeds are expected to reach 1000 km/s or a bit beyond. This results in a reduction of the acceleration time by one to two orders of magnitude. As the other main parameters do not change as much the maximum particle energies get boosted by the same amount and may reach TeV energies for both electrons and protons (see also Bosch-Ramon et al. (2010)). The main interest to have faster shocks moving in dense media is that EP can produce magnetic fluctuations and in fine generate some magnetic field. The magnetic field strength thus produced can be compared with constraints obtained from observations of non-thermal radio emission in a sample of jets (Purser et al. 2016). It can be found that the magnetic field produced by EP accelerated at the termination shock of high mass YSO can partly explain the strength of the equipartition magnetic field deduced from centimetric radio emission of the objects (Araudo et al, in prep).

5 Perspectives

Although the above results are appealing, a lot still remains to be done to properly evaluate the impact of EP on the dynamics of these objects. I see three main issues.

[†] for this object see also Gaches & Offner (2018) for a similar approach although with different assumptions concerning the main EP sources.

5.1 The issue with particle acceleration

As noticed in the above discussions, there are still large uncertainties about which acceleration mechanism dominates in YSO. Also, the power imparted into EP is loosely constrained and need more observational work oriented towards the determination of the key parameters of these acceleration models.

5.2 The issue with particle transport

One major issue is the control of particle propagation from their acceleration sites to their interaction sites. This is a complex modeling. It involves to account for the correct calculation of ionization losses by a correct evaluation of the column density N crossed by the particles (Padovani et al. 2018b; Rab et al. 2017; Padovani et al. 2013). N can vary considerably depending on the magnetic field geometry, hence refined MHD simulations are required to gain knowledge about this parameter. Such an approach has been for instance adopted by Fraschetti et al. (2019) who use a MHD model of M-dwarf magnetosphere to model EP propagation up to planets in the habitable zone. This work also adopted an ad-hoc model for the turbulent component of the magnetic field simply added to the MHD solution. As it may be expected, the EP fluxes at planets sensitively depend on the amplitude of the turbulent component which controls the diffusion coefficient of the particles. Similar ad-hoc models of diffusion coefficients in the context of YSO show a strong impact of propagation effects over the EP flux expected in the accretion disk and hence over the ionization fraction of the different disk layers (Rodgers-Lee et al. 2017).

5.3 Dynamical effects ?

A better knowledge of these two previous issues is not enough. One of the main characteristic of YSO is that these systems are highly transitory, time dependence ultimately connected to the accretion process and hence to the way angular momentum is transferred outwardly. EP acceleration does not escape to this rule and is likely a time-dependent phenomenon which has to find its place in the global dynamics of these objects. A proper account of acceleration processes duty cycles are also necessary to a proper account of feedback on star formation to evaluate the total amount of energy released by YSO in the ISM. In M-dwarfs links with Solar studies are may be more direct because of the absence of any disk but still there time-dependent effects are important to consider if we want to address the impact of EP over planet atmo/magneto-spheres (Fraschetti et al. 2019; Tabataba-Vakili et al. 2016).

5.4 Numerical modelling

If we consider the complexity of the environments considered in young stars, the numerical tools developed over the recent years to investigate multi-scale particle acceleration and transport in space plasma and high-energy Astrophysics communities (Marcowith et al. 2016) can only bring some progress in this field of research.

6 Conclusions

In conclusion we see from this short review that the role of EP in YSO and in more evolved stars needs to be clarified for several purposes. 1) Explain some observables (high ionization rates, synchrotron radiation from jets, non-thermal radio emission associated with magnetospheric activity, meteoritic element abundances). It appears that, unless for some very particular environment, galactic CR can not explain these observables completely. 2) Explore their role in the dynamics of these objects, in particular in the accretion process and the jet ejection. 3) Evaluate their potential impact over planet formation and planet atmospheres (thus on the appearance of life). Three main issues which still preclude any strong progress in the field have been listed: particle acceleration, particle transport, time-dependent effects. These uncertain aspects need some specific observations to constrain the main model parameters. The advent of powerful numerical tools, especially in the space plasma community, to investigate particle acceleration and transport could be applied to these systems.

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References

Ainsworth, R. E., Scaife, A. M. M., Ray, T. P., et al. 2014, The Astrophysical Journal, 792, L18

Andre, P. 1996, in Astronomical Society of the Pacific Conference Series, Vol. 93, Radio Emission from the Stars and the Sun, ed. A. R. Taylor & J. M. Paredes, 273–284

Anglada, G., Rodríguez, L. F., & Carrasco-González, C. 2018, A&A Rev., 26, 3

Armitage, P. J. 2011, Annual Review of Astronomy and Astrophysics, 49, 195

Bally, J. 2016, Annual Review of Astronomy and Astrophysics, 54, 491

Bosch-Ramon, V., Romero, G. E., Araudo, A. T., & Paredes, J. M. 2010, A&A, 511, A8

Ceccarelli, C., Dominik, C., López-Sepulcre, A., et al. 2014, ApJ, 790, L1

Cleeves, L. I., Adams, F. C., Bergin, E. A., & Visser, R. 2013, ApJ, 777, 28

de Gouveia Dal Pino, E. M., Piovezan, P. P., & Kadowaki, L. H. S. 2010, Astronomy and Astrophysics, 518, A5

del Valle, M. V., Romero, G. E., Luque-Escamilla, P. L., Martí, J., & Ramón Sánchez-Sutil, J. 2011, The Astrophysical Journal, 738, 115

Dermer, C. D., Miller, J. A., & Li, H. 1996, The Astrophysical Journal, 456, 106

Emslie, A. G., Dennis, B. R., Shih, A. Y., et al. 2012, ApJ, 759, 71

Favata, F., Flaccomio, E., Reale, F., et al. 2005, The Astrophysical Journal Supplement Series, 160, 469

Favre, C., López-Sepulcre, A., Ceccarelli, C., et al. 2017, A&A, 608, A82

Feigelson, E. D., Broos, P., Gaffney, James A., I., et al. 2002, The Astrophysical Journal, 574, 258

Feigelson, E. D. & Montmerle, T. 1999, Annual Review of Astronomy and Astrophysics, 37, 363

Fontani, F., Ceccarelli, C., Favre, C., et al. 2017, A&A, 605, A57

Fraschetti, F., Drake, J. J., Alvarado-Gómez, J. D., et al. 2019, The Astrophysical Journal, 874, 21

Gaches, B. A. L. & Offner, S. S. R. 2018, The Astrophysical Journal, 861, 87

Getman, K. V., Feigelson, E. D., Micela, G., et al. 2008, The Astrophysical Journal, 688, 437

Gounelle, M., Chaussidon, M., & Rollion-Bard, C. 2013, ApJ, 763, L33

Jacquet, E. 2019, A&A, 624, A131

Klein, K.-L. & Dalla, S. 2017, Space Science Reviews, 212, 1107

Krucker, S., Hudson, H. S., Glesener, L., et al. 2010, The Astrophysical Journal, 714, 1108

Lammer, H., Lichtenegger, H. I. M., Kulikov, Y. N., et al. 2007, Astrobiology, 7, 185

Marcowith, A., Bret, A., Bykov, A., et al. 2016, Reports on Progress in Physics, 79, 046901

Nakamura, F. & Li, Z.-Y. 2007, The Astrophysical Journal, 662, 395

Offner, S. S. R. & Chaban, J. 2017, The Astrophysical Journal, 847, 104

Padovani, M., Galli, D., Ivlev, A. V., Caselli, P., & Ferrara, A. 2018a, A&A, 619, A144

Padovani, M., Hennebelle, P., & Galli, D. 2013, Astronomy and Astrophysics, 560, A114

Padovani, M., Ivlev, A. V., Galli, D., & Caselli, P. 2018b, A&A, 614, A111

Padovani, M., Marcowith, A., Hennebelle, P., & Ferrière, K. 2016, A&A, 590, A8

Podio, L., Lefloch, B., Ceccarelli, C., Codella, C., & Bachiller, R. 2014, A&A, 565, A64

Purser, S. J. D., Lumsden, S. L., Hoare, M. G., et al. 2016, MNRAS, 460, 1039

Rab, C., Güdel, M., Padovani, M., et al. 2017, Astronomy and Astrophysics, 603, A96

Raga, A. C., Velázquez, P. F., Cantó, J., & Masciadri, E. 2002, Astronomy and Astrophysics, 395, 647

Rodgers-Lee, D., Taylor, A. M., Ray, T. P., & Downes, T. P. 2017, Monthly Notices of the Royal Astronomical Society, 472, 26

Rodríguez-Kamenetzky, A., Carrasco-González, C., Araudo, A., et al. 2017, ApJ, 851, 16

Rodríguez-Kamenetzky, A., Carrasco-González, C., Araudo, A., et al. 2016, ApJ, 818, 27

Tabataba-Vakili, F., Grenfell, J. L., Grießmeier, J. M., & Rauer, H. 2016, Astronomy and Astrophysics, 585, A96

Tatischeff, V., Duprat, J., & de Séréville, N. 2014, ApJ, 796, 124

Vidotto, A. A., Jardine, M., Morin, J., et al. 2013, Astronomy and Astrophysics, 557, A67