Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **464,** L90–L94 (2017)
Advance Access publication 2016 September 15
doi:10.1093/mnrasl/slw187

On the existence of accretion-driven bursts in massive star formation

D. M.-A. Meyer,[1★] E. I. Vorobyov,[2,3] R. Kuiper[1] and W. Kley[1]

[1] *Institut für Astronomie und Astrophysik, Universität Tübingen, Auf der Morgenstelle 10, D-72076 Tübingen, Germany*
[2] *Department of Astrophysics, The University of Vienna, Vienna A-1180, Austria*
[3] *Research Institute of Physics, Southern Federal University, Stachki 194, Rostov-on-Don 344090, Russia*

Accepted 2016 September 13. Received 2016 September 10; in original form 2016 June 21

ABSTRACT

Accretion-driven luminosity outbursts are a vivid manifestation of variable mass accretion on to protostars. They are known as the so-called FU Orionis phenomenon in the context of low-mass protostars. More recently, this process has been found in models of primordial star formation. Using numerical radiation hydrodynamics simulations, we stress that present-day forming massive stars also experience variable accretion and show that this process is accompanied by luminous outbursts induced by the episodic accretion of gaseous clumps falling from the circumstellar disc on to the protostar. Consequently, the process of accretion-induced luminous flares is also conceivable in the high-mass regime of star formation and we propose to regard this phenomenon as a general mechanism that can affect protostars regardless of their mass and/or the chemical properties of the parent environment in which they form. In addition to the commonness of accretion-driven outbursts in the star formation machinery, we conjecture that luminous flares from regions hosting forming high-mass stars may be an observational implication of the fragmentation of their accretion discs.

Key words: stars: flare – stars: massive.

1 INTRODUCTION

Stars form in reservoirs of gas and dust, which collapse under their own gravity. However, a significant fraction of pre-stellar gas, thanks to the conservation of the gas net angular momentum, lands on to a centrifugally balanced circumstellar disc rather than falling directly on to the forming protostar. The manner in which matter accretes from the disc on to the star is still poorly understood and, notably, early spherical collapse models (Larson 1969; Shu 1977) that neglect the disc formation phase cannot explain the variety of mass accretion rates observed in present-day star-forming regions (Vorobyov 2009). In particular, these models yield accretion luminosities that are factors of 10−100 greater than the mean luminosity measured for nearby star-forming regions.

This so-called luminosity problem (Kenyon et al. 1990) can be solved if the accretion history on to the protostar is not smooth or quasi-constant, as predicted by spherical collapse models, but highly time-variable, as it naturally occurs in self-consistent models that follow the transition from clouds to protostellar discs (Dunham & Vorobyov 2012). In these models, protostars spend most of their time in the quiescent phase with low rate of accretion, which is interspersed with short but intense accretion bursts (see Vorobyov & Basu 2006, 2010; Machida, Inutsuka & Matsumoto 2011; Zhu et al. 2012; Vorobyov & Basu 2015). Spectacular examples of these burst systems are a special class of young stars called FU Orionis objects, which display outbursts of a factor of hundreds in luminosity which last several decades to hundreds of years. Such flares are thought to be due to drastic increases in the mass accretion rate of such young stars (Kley & Lin 1996).

Until recently, it was thought that FU-Orionis-type accretion and luminosity bursts were constrained to occur in the solar mass regime of present-day star formation (Audard et al. 2014). However, recent numerical hydrodynamics simulations of primordial disc formation around the first very massive stars have also revealed the presence of accretion bursts caused by disc gravitational fragmentation followed by rapid migration of the fragments on to the protostar (Stacy, Greif & Bromm 2010; Greif et al. 2012; Smith et al. 2012; Vorobyov, DeSouza & Basu 2013; Hosokawa et al. 2016). These studies have revealed highly variable protostellar accretion with multiple bursts, exceeding in numbers their present-day counterparts (DeSouza & Basu 2015). The same process of bursts driven by disc fragmentation operates around primordial supermassive stars, relaxing the ultraviolet photon output and enabling the stellar growth to the limit where general relativistic instability results in the formation of supermassive black holes (Sakurai et al. 2016).

Consequently, the emerging question is, how universal is variable accretion with episodic bursts in star formation and whether it can be associated with a unique physical mechanism? Time variability of accretion on to present-day massive stars at the early phase of their formation is a known process (Krumholz, Klein & McKee 2007; Peters et al. 2010; Kuiper et al. 2011; Klassen et al. 2016). Those

★ E-mail: dominique.meyer@uni-tuebingen.de

studies interpret this phenomenon as a natural consequence of the three-dimensional nature of their self-gravitating numerical simulations, while Kuiper & Yorke (2013) explains it by the interplay between mass accretion, stellar evolution, and radiative feedback. They report how asymmetries can develop in self-gravitating discs and generate an azimuthal anisotropy in the accretion flow on to the protostars. One can particularly notice that in addition to its variable character, it is interspersed with several accretion peaks (see fig. 4 of Klassen et al. 2016). In the above-cited references, the sharp increases of the accretion rate are generated in simulations assuming different pre-stellar core masses, ratio of kinetic by gravitational energy β, assuming either a *rigidly* rotating cloud or a turbulent pre-stellar core.

The study of a maser outflow in the high-mass star-forming region W75N equally conjectures that 'short-lived outflows in massive protostars are probably related to episodic increases in the accretion rates, as observed in low-mass star formation' (Carrasco-González et al. 2015). Additionally, a luminosity outburst of the massive ($\approx$20 $M_\odot$) young star S255IR-NIRS3 was reported in Fujisawa et al. (2015) by means of 6.7 GHz methanol maser emission. This emission line has been discovered by Menten (1991) and constitutes today a well-known tracer of high-mass star-forming regions (see Bartkiewicz, Szymczak & van Langevelde 2016, and references therein). Recent observation of the same object show brightness variations that resemble strongly FU-Orionis-type outbursts (Stecklum et al. 2016).

Motivated by the above listed numerical studies and observational arguments, we continue to investigate the burst phenomenon in the high-mass regime of star formation. We follow existing models showing accretion spikes in high-mass star formation, further analyse their nature in the context of the star–disc evolution, and conjecture on possible observational implications. This study is organized as follows. In Section 2, we review the methods that we utilize to carry out our high-resolution self-gravity radiation-hydrodynamical simulation of the formation and evolution of a disc surrounding a growing present-day massive protostar generated by the collapse of a *non-rigidly* rotating pre-stellar core. Our outcomes are presented and discussed in Section 3. Particularly, our model also generates such outbursts and we show that they are caused by the rapid migration of disc fragments on to the protostar. Finally, we conclude on their significances in Section 4.

2 NUMERICAL SIMULATION

We perform a 3D numerical radiation hydrodynamics simulation with the PLUTO code (Mignone et al. 2007, 2012) that has been augmented with several physics modules for (i) self-gravity of the gas and (ii) a careful treatment of the protostellar irradiation feedback (Kuiper et al. 2010a; Kuiper & Klessen 2013). Our model has been carried out using a spherical coordinate system (r, θ, ϕ) mapped with a grid of size $[r_{\min}, r_{\max}] \times [0, \pi/2] \times [0, 2\pi]$ that is made of $128 \times 21 \times 128$ cells, respectively. The grid resolution expands logarithmically in the radial direction, scales as $\cos(\theta)$ in the polar direction, is uniform in the azimuthal direction and assumes mid-plane symmetry about $\theta = \pi/2$, such that it allows us to reach sub-au spatial resolution in the inner region of the disc. The dynamics of the collapse and the accretion flow is calculated in the frame of reference of the fixed protostar that is considered to be evolving inside a static, semipermeable sink cell of initial mass $\approx 10^{-3}$ $M_\odot$ with a radius $r_{\min} = 10$ au such that the mass flux through it represents the protostellar accretion rate $\dot{M}$ on to the stellar surface. The creation of other sink cells is not allowed. As described in Kuiper et al. (2010b), we utilize $\dot{M}$ to self-consistently update the stellar mass and interpolate the pre-calculated protostellar evolutionary tracks of Hosokawa & Omukai (2009) to use them as boundary conditions for the radiation transport module.

We follow the gravitational collapse of an $M_c = 100$ $M_\odot$ pre-stellar core of outer radius $r_{\max} = 0.1$ pc. The radiation is regulated using the dust opacity prescription of Laor & Draine (1993) while the constant gas opacity is taken to be $\kappa_g = 0.01$ cm^2 g^{-1}. This hybrid radiation transport method allows us to carefully treat disc thermodynamics and to generate the dust sublimation front in massive protostellar accretion discs (cf. Vaidya, Fendt & Beuther 2009). Our pre-stellar core has the canonical radial density distribution $\rho(r) \propto r^{-3/2}$. We do not consider a rigidly rotating core but impose a radial angular momentum distribution $\Omega(R) \propto R^{-3/4}$ with $R = r\sin(\theta)$ the cylindrical radius. We impose a ratio of rotational to gravitational energy $\beta = 4$ per cent, its initial temperature is uniformly taken to $T_g = 10$ K and we set its pressure assuming that the gas is at solar metallicity and obeys an ideal equation of state. The dust temperature T_d is considered as equal to the gas temperature $T_g = T_d$. The collapse of the core and the evolution of the accretion disc is followed during 30 kyr.

3 RESULTS

3.1 Episodic accretion of dense gaseous clumps

The mid-plane density field from the simulation (in g cm^{-3}) is shown in Fig. 1 at different evolutionary times (in kyr). While panel (a) represents an overview of the whole disc region (where material orbits the star with approximately Keplerian velocity), panels (b)–(d) are zooms focusing on the inner region of the disc. The first snapshot (a) shows the circumstellar medium of the protostar at a time 18.10 kyr. In addition to the gas that is being accreted in the innermost 50 au of the disc, it develops inhomogeneities by gravitational instability that take the form of spiral arms terminated by dense blobs of gas orbiting at radii 450–800 au from the protostar. One of those Truelove-resolved arms ($\lambda/\Delta \sim 6$–8, where λ is the Jeans length and Δ is the grid cell size; see Truelove et al. 1998) experiences a local increase in density and develops an overdense clump of circumstellar material at a radial distance of $\approx$200 au to the central star. This is how fragmentation occurs at those radii ($\geq$150 au) predicted by the analytic study of Kratter & Matzner (2006), despite the fact that only marginal fragmentation for discs like the one around our $\approx$4.5 $M_\odot$ protostar is foreseen (see also Fig. 3b).

By means of angular momentum transfer to the closest spiral arm, the clump migrates towards the protostar. At the onset of migration (Fig. 1a), the closest distance to which the clump can fall, assuming angular momentum conservation, is $\sim$2000 $R_\odot$, and it decreases to $\sim$260 $R_\odot$ (Fig. 1b) before to become comparable to the stellar radius of $\sim$90 $R_\odot$ shortly before entering the sink cell. This value is certainly an upper limit because the angular momentum of the clump decreases during its inward migration thanks to the gravitational interaction with the closest spiral arm (the gravitational torque acting on the clump is negative), as was shown in application to low-mass star formation by Vorobyov & Basu (2006). As a consequence, we expect the clump to fall directly on to the star. However, if the gas temperature in the clump interior exceeds 2000 K, the clump will further contract owing to dissociation of molecular hydrogen. In this case, not captured by our numerical simulations due to limited numerical resolution, its

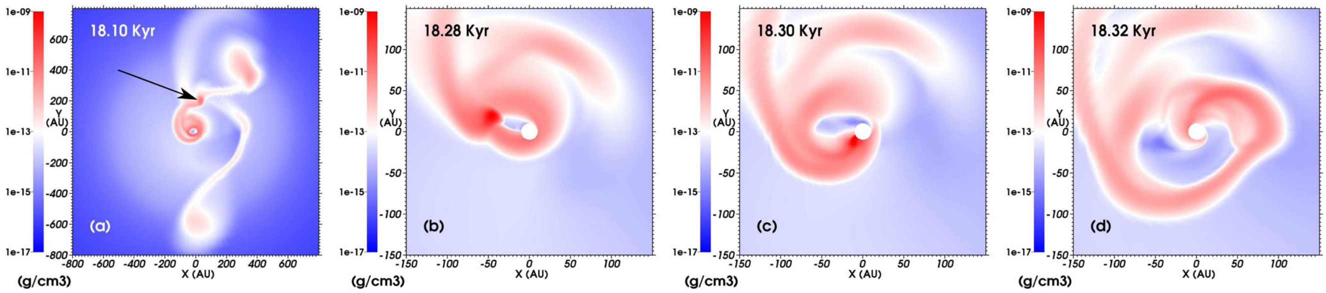

Figure 1. Mid-plane density in the centre of the computational domain around the time of the first outburst. (a) The region within 800 au when a clump forms in a spiral arm ∼200 au away from the protostar, at a time 18.10 kyr. Panel (b and c) display zooms to illustrate the migration and accretion of a part of the clump at times 18.28, 18.30, and 18.32 kyr, respectively. The density is plotted in g cm^{-3} on a logarithmic scale and the size of the panels is in au.

subsequent evolution will depend on the amount of rotational energy in the clump. By extrapolation of the clump properties formed in discs around solar-mass stars showing that about half of the clumps are rotationally supported (see Vorobyov 2016), we expect that part of the clump material will retain in the form of a disc/envelope around the newly formed protostar. This material can still be lost on to the central protostar via the Roche lobe creating an accretion burst though of lesser amplitude, as was shown in Nayakshin & Lodato (2012). Furthermore, high-resolution studies of low-mass and primordial star formation showed that further fragmentation may happen within in the innermost disc regions occupied by our sink cell, likely triggered by already existing outer fragments or efficient H_2 cooling and collisionally induced emission (see Greif et al. 2012; Meru 2015). If fragmentation in the inner disc occurs also in the case of high-mass star formation, this may provoke the formation of a pattern of very small clumps which complex mutual gravitational interactions can make them merging together, orbiting on to the protostar or being dynamically ejected away. This would modify the physics of accretion and the accretion luminosity of the protostar, however, heavy clumps migrating very rapidly will still fall directly on to the stellar surface. To follow this process in detail, however, a much smaller (than 10 au) sink cell and, as a consequence, much longer integration times are needed. We leave this investigation for a subsequent study.

At time 18.28 kyr, the clump is at about 60 au from the protostar (Fig. 1b) and its density reaches $\geq 10^{-9}$ g cm^{-3}. The self-gravitating clump adopts a slightly elongated shape due to the gravitational influence of the massive protostar. At time 18.30 kyr (Fig. 1c), the stretched clump starts wrapping around the sink cell. A part of its material is accreted on to the protostar, and, consequently, it affects the star's accretion luminosity $L_{\rm acc} \propto GM_{\star}\dot{M}/R_{\star}$ (see Section 3.2). When the clump starts migrating towards the star its radius is 20 au. As the clump approaches the sink cell, its mass has decreased to $\simeq 0.7\,{\rm M}_{\odot}$ and its Hill radius decreases from approximately 35 au to $\lesssim 10$ au, causing the clump to lose part of its mass in the diffuse outer envelope. Finally, about 0.55 $\rm M_{\odot}$ is accreted through the sink cell. After time 18.32 kyr (Fig. 1d), the structure of the density field around the sink cell is that of a spiral of unaccreted dense gas material.

This scenario is episodic in the disc evolution and repeats itself at a time about 21.00 kyr when another clump is similarly accreted. The time interval between recurrent accretion bursts can be determined as the time needed to replenish the disc material lost during the last accretion event $t_{\rm repl} = M_{\rm cl}/\dot{M}_{\rm infall}$, where $M_{\rm cl}$ is the clump mass and $\dot{M}_{\rm infall}$ the mass infall rate on to the disc from the collapsing envelope (see Section 3.2). For $M_{\rm cl} \sim 0.55\,{\rm M}_{\odot}$ and $\dot{M}_{\rm infall} = (2\text{–}3) \times 10^{-4}\,{\rm M}_{\odot}\ {\rm yr}^{-1}$, typical values for the time of the bursts, the characteristic time of recurrent outbursts is $t_{\rm repl} \approx 2\text{–}2.5$ kyr. If $t_{\rm repl}$ is regarded as the time required to increase the disc mass to the limit when the disc fragments, i.e. as the fragmentation time-scale, then the clump migration time-scale is much shorter than the fragmentation time-scale $t_{\rm repl}$. This is indeed evident from Fig. 1.

3.2 Accretion-induced strong outbursts

The accretion rate $\dot{M}$ on to the protostar exhibits rapid variations after the disc formation at about 4 kyr (see Fig. 2a). Comparing $\dot{M}$ measured at $r_{\rm min} = 10$ au with the smooth infall rate $\dot{M}_{\rm infall}$ from the envelope on to the disc measured at $r = 3000$ au, it becomes evident that the oscillations of $\dot{M}$ from about 10^{-6} to about $10^{-3}\,{\rm M}_{\odot}\ {\rm yr}^{-1}$ are caused by the disc gravitational instability when filaments and spiral arms of different density and length converge towards the protostar. This correlation between the strength of disc gravitational instability and the protostellar accretion variability is well known in low-mass star formation (Dunham & Vorobyov 2012; Vorobyov & Basu 2015). The envelope, on the other hand, has a smooth density and velocity structure, and its infall rate that gradually increases with time for the initial free-fall time of the mass reservoir. Note also that the self-similar solution for the singular isothermal sphere (Shu 1977) computed as the mean isothermal infall rate at $r = 3000$ au, underestimates the accretion on to the protostar by about an order of magnitude (Fig. 2a), as previously noticed in the context of low-mass and high-mass star formation, see Vorobyov (2009) and Banerjee & Pudritz (2007), respectively.

At times 18.29 and 21.30 kyr the accretion of parts of the heaviest clumps occurs. The total luminosity of the protostar, i.e. the sum of its photospheric luminosity $L_{\star}$ and its accretion luminosity $L_{\rm acc}$ rises simultaneously (see Fig. 2b). The first luminosity outburst is particularly strong reaching in magnitude $5 \times 10^5\,{\rm L}_{\odot}$. The second burst is notably weaker because the radius of the protostar has greatly increased after the first one. These accretion and luminosity outbursts are a direct consequence of the accretion of in-spiralling clumps that fall on to the protostar because of the loss of angular momentum that has been exchanged with other structures of the disc such as spiral arms, filaments, and arcs. In Fig. 3, we present various disc and stellar properties around the time of the first burst. The accretion rate exhibits a rapid increase from $\dot{M} \sim 10^{-3}\,{\rm M}_{\odot}\ {\rm yr}^{-1}$ to $\dot{M} \approx 10^{-1}\,{\rm M}_{\odot}\ {\rm yr}^{-1}$ over a time interval of $\approx$10 yr, while the protostar experiences a flare reaching $\geq 5 \times 10^5\,{\rm L}_{\odot}$ (Fig. 3a). As the protostar accretes the clump, its mass increases while the disc mass decreases by the amount of mass of the accreted clump. This results in a remarkable step-like decrease of the disc-to-star mass ratio (see Fig. 3b), making the disc temporarily stable to gravitational fragmentation. It takes a few several kyr for the disc to accrete additional mass from the collapsing envelope and produce another

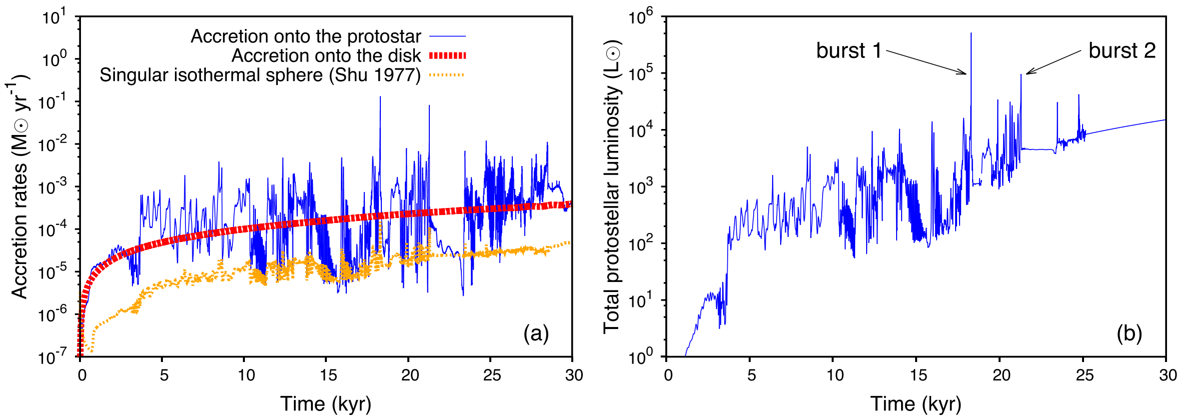

Figure 2. Left: accretion rate on to the protostar and mass infall rate on to the disc (in $M_\odot$ yr^{-1}). Right: total luminosity of the protostar (in $L_\odot$).

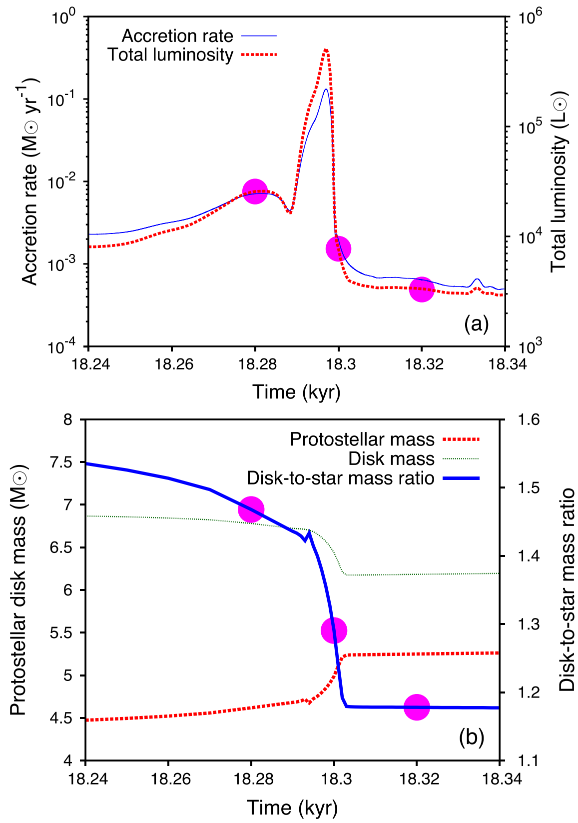

Figure 3. Upper panel: as in Fig. 2 during the time interval corresponding to the first accretion-induced outburst. Bottom panel: protostellar mass ($M_\odot$) and disc-to-star mass. The magenta dots mark the times of the zooms in Fig. 1(b)–(d).

similar fragmentation episode. This phenomenon repeats for as long as there is enough material in the envelope to replenish the disc mass, as was previously found for low-mass (Vorobyov 2010) and primordial star formation (Vorobyov et al. 2013; Hosokawa et al. 2016).

4 DISCUSSION AND CONCLUSION

We have confirmed the presence of strong peaks in the variable accretion history of high-mass protostars, already present in the literature for a wide range of initial conditions of the pre-stellar core. All models have a standard initial density distribution $\propto r^{-3/2}$ that is assumed in the absence of corresponding observations, except $\propto r^{-2}$ in Kuiper et al. (2011) and Kuiper & Yorke (2013). All rotating models preceding our study assumed cores in solid-body rotation. Radiation-hydrodynamics (with and without turbulence) and magnetohydrodynamics simulations include, with initial conditions in terms of of $M_{\rm c}$ and β-ratio, 100–200 $M_\odot$ without rotation (Krumholz et al. 2007), 100 $M_\odot$ with 2 per cent (Krumholz et al. 2009), 120 $M_\odot$ with a few per cent (Kuiper et al. 2011) 1000 $M_\odot$ with 5 per cent (Peters et al. 2010), 100 $M_\odot$ with 0.04–20 per cent (Seifried et al. 2011), and 100; 200 $M_\odot$ with 10.5; 5.3 per cent (Klassen et al. 2016), respectively, while we use 100 $M_\odot$ with 4 per cent. Our higher spatial resolution in the inner disc allows us to explicitly capture the fall of forming circumstellar clumps rather than modelling overdense filaments in the disc that wrap on to the star. It enables to study this process, well known in the low-mass and primordial regime of star formation as the so-called episodic accretion-driven outbursts, which we conclude to be also present in the high-mass regime of contemporary star formation. To confirm this result, we have performed preliminary simulations varying the initial rotation curves of the pre-stellar core. In the subsequent studies, numerical simulations with a smaller sink cell are needed to determine more in detail the final fate of the accreted clumps. However, we expect that the protostellar accretion history remains quantitatively similar in models with sink radii varied by a factor of 2, as was earlier shown for low-mass star formation (see Vorobyov & Basu 2015, and references therein).

We obtain the protostellar accretion history which is highly time-variable and shows sudden accretion spikes, as was found in several previous models of massive star-forming pre-stellar cores and interpreted as caused by azimuthal asymmetries in the accretion flow. The higher spatial resolution of our model reveals that, in addition to variable accretion indeed caused by the asymmetric character of its disc, the growing massive protostar can accrete material of gaseous clumps formed in spiral arms owing to disc gravitational fragmentation, which rapidly migrate towards the protostar and induce luminous protostellar outbursts. A similar rapid migration of dense clumps is present in gravitationally unstable discs around solar-mass stars, in primordial discs around the first stars and when high-mass planets form (Baruteau, Meru & Paardekooper 2011; Vorobyov 2013). Our work indicates that this also applies to the high-mass regime of star formation, which implies a change in the paradigm which, to the best of our knowledge, considered episodic accretion-induced protostellar outbursts as inherent to low-mass and primordial star formation only. Our study shows that it concerns star formation in general, for a wide range of the physical properties such as the initial mass, β-ratio, angular momentum distribution or chemical composition of the parent environment in which stars form.

It supports the consideration of star formation as a process ruled by a common set of mechanisms leading to circumprotostellar structures similarly organized, but scaled-up with respect to each other as a function of the initial properties of their parental pre-stellar cores, as observationally suggested (Shepherd & Churchwell 1996; Fuente et al. 2001; Testi 2003; Keto & Zhang 2010; Johnston et al. 2015). Finally, we propose to consider flares from high-mass protostellar objects as a possible tracer of the fragmentation of their accretion discs. This may apply to the young star S255IR-NIRS3 that has recently been associated with a 6.7 GHz methanol maser outburst (Fujisawa et al. 2015; Stecklum et al. 2016), but also to the other regions of high-mass star formation from which originated similar flares (Menten 1991) and which are showing evidences of accretion flow associated with massive protostars, see e.g. in W3(OH) (Hirsch et al. 2012), W51 (Keto & Klaassen 2008; Zapata et al. 2009), and W75 (Carrasco-González et al. 2015).

ACKNOWLEDGEMENTS

We thank the anonymous reviewer for his valuable comments which improved the quality of the paper. This study was conducted within the Emmy Noether research group on 'Accretion Flows and Feedback in Realistic Models of Massive Star Formation' funded by the German Research Foundation under grant no. KU 2849/3-1. EIV acknowledges support from the Austrian Science Fund (FWF) under research grant I2549-N27 and RFBR grant 14-02-00719.

REFERENCES

Audard M. et al., 2014, Protostars and Planets VI. Univ. Arizona Press, Tucson, AZ, p. 387
Banerjee R., Pudritz R. E., 2007, ApJ, 660, 479
Bartkiewicz A., Szymczak M., van Langevelde H. J., 2016, A&A, 587, A104
Baruteau C., Meru F., Paardekooper S.-J., 2011, MNRAS, 416, 1971
Carrasco-González C. et al., 2015, Science, 348, 114
DeSouza A. L., Basu S., 2015, MNRAS, 450, 295
Dunham M. M., Vorobyov E. I., 2012, ApJ, 747, 52
Fuente A., Neri R., Martín-Pintado J., Bachiller R., Rodríguez-Franco A., Palla F., 2001, A&A, 366, 873
Fujisawa K., Yonekura Y., Sugiyama K., Horiuchi H., Hayashi T., Hachisuka K., Matsumoto N., Niinuma K., 2015, Astron. Telegram, 8286
Greif T. H., Bromm V., Clark P. C., Glover S. C. O., Smith R. J., Klessen R. S., Yoshida N., Springel V., 2012, MNRAS, 424, 399
Hirsch L. et al., 2012, ApJ, 757, 113
Hosokawa T., Omukai K., 2009, ApJ, 691, 823
Hosokawa T., Hirano S., Kuiper R., Yorke H. W., Omukai K., Yoshida N., 2016, ApJ, 824, 119
Johnston K. G. et al., 2015, ApJ, 813, L19
Kenyon S. J., Hartmann L. W., Strom K. M., Strom S. E., 1990, AJ, 99, 869
Keto E., Klaassen P., 2008, ApJ, 678, L109
Keto E., Zhang Q., 2010, MNRAS, 406, 102
Klassen M., Pudritz R. E., Kuiper R., Peters T., Banerjee R., 2016, ApJ, 823, 28
Kley W., Lin D. N. C., 1996, ApJ, 461, 933
Kratter K. M., Matzner C. D., 2006, MNRAS, 373, 1563
Krumholz M. R., Klein R. I., McKee C. F., 2007, ApJ, 656, 959
Krumholz M. R., Klein R. I., McKee C. F., Offner S. S. R., Cunningham A. J., 2009, Science, 323, 754
Kuiper R., Klessen R. S., 2013, A&A, 555, A7
Kuiper R., Yorke H. W., 2013, ApJ, 772, 61
Kuiper R., Klahr H., Dullemond C., Kley W., Henning T., 2010a, A&A, 511, A81
Kuiper R., Klahr H., Beuther H., Henning T., 2010b, ApJ, 722, 1556
Kuiper R., Klahr H., Beuther H., Henning T., 2011, ApJ, 732, 20
Laor A., Draine B. T., 1993, ApJ, 402, 441
Larson R. B., 1969, MNRAS, 145, 271
Machida M. N., Inutsuka S.-I., Matsumoto T., 2011, ApJ, 729, 42
Menten K. M., 1991, ApJ, 380, L75
Meru F., 2015, MNRAS, 454, 2529
Mignone A., Bodo G., Massaglia S., Matsakos T., Tesileanu O., Zanni C., Ferrari A., 2007, ApJS, 170, 228
Mignone A., Zanni C., Tzeferacos P., van Straalen B., Colella P., Bodo G., 2012, ApJS, 198, 7
Nayakshin S., Lodato G., 2012, MNRAS, 426, 70
Peters T., Banerjee R., Klessen R. S., Mac Low M.-M., Galván-Madrid R., Keto E. R., 2010, ApJ, 711, 1017
Sakurai Y., Vorobyov E. I., Hosokawa T., Yoshida N., Omukai K., Yorke H. W., 2016, MNRAS, 459, 1137
Seifried D., Banerjee R., Klessen R. S., Duffin D., Pudritz R. E., 2011, MNRAS, 417, 1054
Shepherd D. S., Churchwell E., 1996, ApJ, 472, 225
Shu F. H., 1977, ApJ, 214, 488
Smith R. J., Hosokawa T., Omukai K., Glover S. C. O., Klessen R. S., 2012, MNRAS, 424, 457
Stacy A., Greif T. H., Bromm V., 2010, MNRAS, 403, 45
Stecklum B., Caratti o Garatti A., Cardenas M. C., Greiner J., Kruehler T., Klose S., Eisloeffel J., 2016, Astron. Telegram, 8732
Testi L., 2003, in De Buizer J. M., van der Bliek N. S., eds, ASP Conf. Ser. Vol. 287, Galactic Star Formation Across the Stellar Mass Spectrum. Astron. Soc. Pac., San Francisco, p. 163
Truelove J. K., Klein R. I., McKee C. F., Holliman II J. H., Howell L. H., Greenough J. A., Woods D. T., 1998, ApJ, 495, 821
Vaidya B., Fendt C., Beuther H., 2009, ApJ, 702, 567
Vorobyov E. I., 2009, ApJ, 704, 715
Vorobyov E. I., 2010, ApJ, 723, 1294
Vorobyov E. I., 2013, A&A, 552, A129
Vorobyov E. I., 2016, A&A, 590, A115
Vorobyov E. I., Basu S., 2006, ApJ, 650, 956
Vorobyov E. I., Basu S., 2010, ApJ, 714, L133
Vorobyov E. I., Basu S., 2015, ApJ, 805, 115
Vorobyov E. I., DeSouza A. L., Basu S., 2013, ApJ, 768, 131
Zapata L. A., Ho P. T. P., Schilke P., Rodríguez L. F., Menten K., Palau A., Garrod R. T., 2009, ApJ, 698, 1422
Zhu Z., Hartmann L., Nelson R. P., Gammie C. F., 2012, ApJ, 746, 110