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Modeling the prestellar cores in Ophiuchus

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Abstract. We present the first results from a project to model the prestellar cores in Ophiuchus, using initial conditions constrained as closely as possible by observation. The prestellar cores in Ophiuchus appear to be evolving in isolation — in the sense that the timescale on which an individual prestellar core collapses and fragments is estimated to be much shorter than the timescale on which it is likely to interact dynamically with another core. Therefore it is realistic to simulate individual cores separately, and this in turn makes it feasible (a) to perform multiple realisations of the evolution of each core (to allow for uncertainties in the initial conditions which persist, even for the most comprehensively observed cores), and (b) to do so at high resolution (so that even the smallest protostars are well resolved). The aims of this project are (i) to address how best to convert the observations into initial conditions; (ii) to explore, by means of numerical simulations, how the observed cores are likely to evolve in the future; (iii) to predict the properties of the protostars that they will form (mass function, multiplicity statistics, etc.); and (iv) to compare these properties with the properties of the observed pre-Main Sequence stars in Ophiuchus. We find that if the observed non-thermal velocities in the Ophiuchus prestellar cores are attributed to purely solenoidal turbulence, they do not fragment; they all collapse to form single protostars. If the non-thermal velocities are attributed to a mixture of solenoidal and compressive turbulence, multiple systems form readily. The turbulence first generates a network of filaments, and material then tends to flow along the filaments, at first into a primary protostar, and then onto a compact accretion disc around this protostar; secondary protostars condense out of the material flowing into the disc along the filaments. If the turbulence is purely solenoidal, but part of the non-thermal velocity dispersion is attributed to solid-body rotation, then again multiple systems form readily, but the pattern of fragmentation is quite different. A primary protostar forms near the centre of the core, and then an extended accretion disc forms around the primary protostar, and eventually becomes so massive that it fragments to produce low-mass secondaries; these frequently end up in hierarchical multiple systems.

Keywords. star formation, binary formation, prestellar cores, turbulence

1. Introduction

At an estimated distance between 120 and 140 pc, Ophiuchus is one of the nearest sites of ongoing, mildly clustered star formation, and it has been extensively observed at many different wavelengths. The aim of this project is to explore whether these observations can be used to inform the initial conditions for simulations of the evolution of the observed prestellar cores in Ophiuchus, and to compare the resulting protostars with the observed population of protostars and pre-Main Sequence stars in Ophiuchus. Such a project is timely because recent estimates of the mass function of the prestellar cores in Ophiuchus (Motte *et al.* 1998, Johnstone *et al.* 2000, Simpson *et al.* 2010) indicate that it is very similar in shape to the stellar initial mass function, but shifted to higher masses by a factor of order three. This in turn implies that the efficiency of star formation in a prestellar core is $\sim 33\,\%$. It is therefore appropriate to ask how the core mass function maps into the stellar mass function. Since this is a highly non-linear mapping, the only way to explore it is through numerical simulations.

The work of André *et al.* (2007) suggests that the prestellar cores in Ophiuchus evolve more-or-less in isolation. In other words, an individual core collapses and fragments to form a protostar, or a small-N system of protostars, on a timescale that is sufficiently short that the process is complete before the core has time to interact with one of the other cores in the cloud. Therefore we can model an individual core with up to 10,000 SPH particles per $5\,\mathrm{M_{JUPITER}}$. Since protostars significantly less massive than this are unlikely to form, this means that all protostars are extremely well resolved.†

2. Initial conditions

By combining observations of dust continuum emission (Motte André & Neri, 1998; Johnstone *et al.*, 2000; Stanke *et al.*, 2006; Simpson *et al.*, 2010) with observations of molecular-line emission, in particular N_2H^+ $(1-0)$ emission (André *et al.*, 2007) and $HCO^+(1-0)$ emission (Simpson *et al.*, 2010), and with detailed radiation transport modeling (Stamatellos *et al.*, 2007; Simpson *et al.*, 2010), we have estimates – for 43 cores – of the mass, the extent on the sky, the velocity dispersion along the line of sight, the ambient radiation field, and the temperature. Strictly speaking, this is the dust temperature, but it is probably also close to the gas-kinetic temperature. We have most of this information for a further 30+ cores (also in Ophiuchus).

This does not specify the initial conditions exactly. First, even if we constrain the 3D shape of a core to be a triaxial ellipsoid, we do not know the extent along the line of sight. However, Goodwin, Whitworth & Ward-Thompson (2004) suggest that this may not be critical, and therefore we start by taking all the cores to be spherically symmetric, with radius equal to the geometric mean of the projected minor and major axes.

Second we do not know the detailed density profile of a core. For simplicity, we assume that all cores have the density profile of a critical Bonnor-Ebert sphere, since many low-mass prestellar cores appear to approximate to this form. However, that we are not assuming that a core is in hydrostatic balance. In general, the cores are thermally supercritical, i.e. they do not have sufficient thermal pressure to support themselves. We note that the self-gravitational potential energy, moment of inertia, and full width at half maximum for optically thin emission from a critical Bonnor-Ebert sphere are given by

$$-\,\Omega_{\mathrm{CORE}} = \frac{0.732\,G\,M_{\mathrm{CORE}}^2}{R_{\mathrm{CORE}}}, \tag{2.1}$$

$$I_{\mathrm{CORE}} = 0.283\,M_{\mathrm{CORE}}\,R_{\mathrm{CORE}}^2, \tag{2.2}$$

$$D_{\mathrm{FWHM}} = 0.802\,R_{\mathrm{CORE}}. \tag{2.3}$$

Third, we do not know the split of non-thermal energy between (i) statistically isotropic random turbulence, (ii) ordered global rotation, and (iii) ordered in- or out-flow. Further we do not know how the turbulence is split between solenoidal and compressive modes,

† We are here using the term protostar to embrace any object that forms by gravitational instability, on a dynamical timescale, and with an approximately uniform interstellar elemental composition – as distinct from planets, which form by core accretion, on a much longer timescale and with an initially fractionated composition.

whether the rotation is solid-body or differential, and whether the in- or out-flow is homologous or isotropic. These appear to be the most critical issues, and these are the issues that we focus on here.

3. Numerical method

We use the recently developed SPH code SEREN (Hubber *et al.* 2010). Radiative cooling and the associated radiation transport are treated using the method of Stamatellos *et al.* (2007). Sink particles are introduced where the density rises above $\rho_{\rm SINK}$, provided that the condensation at this location is gravitationally bound, and the divergences of the acceleration is negative. We use $\rho_{\rm SINK} = 10^{-9}\,{\rm g\,cm^{-3}}$, so that all protostars are well into their Kelvin-Helmholtz contraction phase before they are replaced with sink particles. We do not include MHD effects (either ideal or non-ideal).

4. Ophiuchus Core B2-MM8

As an illustration of the results, we discuss just two cores. The first core is Ophiuchus B2-MM8. This core is embedded in clump B2. Its estimated mass is $M_{\rm CORE} = 0.77\,{\rm M_\odot}$, and its estimated radius is $R_{\rm CORE} = 0.032\,{\rm pc}$ (corresponding to a full-width at half maximum in optically thin dust continuum emission of 0.026 pc). Its estimated temperature is $T_{\rm CORE} = 10\,{\rm K}$. The estimated ratios of thermal and non-thermal energy to gravitational potential energy are $\alpha_{\rm THERM} = 0.07$ and $\alpha_{\rm NONTH} = 0.11$. The core is therefore presumed to be both thermally and non-thermally supercritical. We have simulated the evolution of this core with the non-thermal energy divided between purely solenoidal turbulence and solid-body rotation in the proportions $1:2$ and $2:1$. The solenoidal turbulence is assumed to have a power spectrum $P_k \propto k^{-4}$. In both cases the central low-angular momentum parts of the core collapse to form a primary protostar, and then an extended accretion disc forms around this. In the case where only one third of the non-thermal energy is attributed to rotation, the disc fragments after about 32 kyr, to form five protostars, and these end up in an hierarchical quintuple system with separations ranging from $\sim 2\,{\rm AU}$ to $\sim 200\,{\rm AU}$. In the case where two thirds of the non-thermal energy is attributed to solid-body rotation, the disc takes longer to form and is more extended. After about 37 kyr, the disc quickly fragments, producing six further protostars; three are ejected, one becomes a close companion to the primary at $\sim 20\,{\rm AU}$, and the remaining two form a close binary system orbiting the primary at $\sim 170\,{\rm pc}$. We emphasise that in all cores that we have simulated with purely solenoidal turbulence, there is no fragmentation. When the turbulence is purely solenoidal, the addition of ordered rotation is essential for fragmentation to occur, and it often leads to the formation of hierarchical multiples.

5. Ophiuchus Core A-MM8

The second core to be discussed is Ophiuchus A-MM8. This core is embedded in clump A. Its estimated mass is $M_{\rm CORE} = 1.28\,{\rm M_\odot}$, and its estimated radius is $R_{\rm CORE} = 0.025\,{\rm pc}$ (corresponding to a full-width at half maximum in optically thin dust continuum emission of 0.020 pc). Its estimated temperature is $T_{\rm CORE} = 11\,{\rm K}$. The estimated ratios of thermal and non-thermal energy to gravitational potential energy are $\alpha_{\rm THERM} = 0.03$

and $\alpha_{\rm NONTH} = 0.02$. The core is therefore presumed to be both thermally and non-thermally supercritical. We have simulated the evolution of this core with the non-thermal energy attributed entirely to turbulence, with a random mix of solenoidal and compressive modes and a power spectrum $P_k \propto k^{-4}$. In this case the collapse of the core leads to the formation of a network of filaments, along which material flows into the central regions. There a primary protostar forms at ~ 10 kyr and grows by accreting the material that flows in along the filaments. There are three main filaments, and because these filaments are not aligned, the inflow brings in material with high angular momentum relative to the primary. This material quickly forms a compact disc (diameter of order 30 AU) around the primary, and the disc then fragments to produce a secondary protostar at ~ 11.4 kyr. The two protostars then compete for the same inflowing material and quickly grow to have similar mass. This is because, as long as the secondary has lower mass, it is better positioned to accrete the inflowing high-angular momentum material (Whitworth *et al.* 1995). At about 13.7 kyr, a third protostar condenses out of the circumbinary disc, but it is quickly driven into a wide and extended orbit, so that it accretes more slowly and remains a somewhat lower-mass object. At ~ 25 kyr, a three-body exchange interaction occurs, leading to the disruption of the original binary; one component is ejected as a single, and the other recoils as a binary system with the lower-mass object.

6. Conclusions

We conclude that the division of non-thermal energy amongst different modes is critical to the outcome of the collapse of a prestellar core, even though the amounts of non-thermal energy are usually quite small compared with the gravitational potential energy. With purely solenoidal turbulence, at the low levels typical of the cores in Ophiuchus (i.e. $\alpha_{\rm NONTH} \lesssim 0.1$), no multiple systems are formed, and therefore we conclude that the non-thermal energy is not usually in purely solenoidal turbulence. We have considered two alternative divisions of the non-thermal energy, which both yield multiple systems, but in different ways. If some of the energy is attributed to ordered solid-body rotation, a massive and extended disc forms around the primary protostar; this then fragments to produce additional protostars, some of which are ejected, and some of which end up in an hierarchical multiple system. If some of the energy is allocated to compressive rather than solenoidal modes, close intermediate-mass binaries form by fragmentation of compact unrelaxed discs that grow from the filaments in which they are embedded; the components often evolve towards equal mass, $q \sim 1$.

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