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ASTRONOMY AND ASTROPHYSICS

Suppression of giant planet formation in stellar clusters

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Abstract. Photoevaporation driven by the ultraviolet radiation from massive stars severely limits the lifetime of protoplanetary discs around stars formed within stellar clusters. I investigate the resulting influence of clustered environments on the probability of giant planet formation, and show that for clusters as rich, or richer than, Orion, the time available for planet formation is likely to be limited to the length of any delay between low mass and high mass star formation. Under popular models for the formation of massive planets, the fraction of stars with giant planets in rich clusters is expected to be substantially suppressed as compared to less clustered star formation environments.

Key words: accretion, accretion discs – solar system: formation – stars: formation – planetary systems – globular clusters: general – open clusters and associations: general

1. Introduction

Almost all low mass stars are born in binary systems (Reipurth & Zinnecker 1993; Ghez et al. 1997; Kohler & Leinert 1998), which are themselves often part of larger stellar clusters (Clarke, Bonnell & Hillenbrand 2000). In some well-studied star forming regions, such as Taurus-Auriga, these are merely loose aggregates of young stars (Gomez et al. 1993), which may be expected to have little influence on the evolution of protoplanetary discs. This is not, however, the case in richer clusters – of which Orion is the nearby prototype – where the radiation and winds from massive stars have a dramatic impact on the local environment (Palla & Stahler 1999; Johnstone & Bertoldi 2000; Chevalier 2000). Planet formation in the discs around low mass stars in such clusters cannot then be considered in isolation.

Observations of discs in Orion suggest that photoevaporation in the radiation field of the massive stars is likely to be the dominant process leading to the destruction of discs (Johnstone, Hollenbach & Bally 1998). In this paper, I assume that this is the case, and discuss the implications for planet formation in clusters of varying richness. The basic conclusion is that the formation of giant planets in clusters richer than Orion is likely to be heavily suppressed, *unless* either they form from prompt hydrodynamic collapse (e.g. Boss 1998), or there is a substantial delay between the onset of low mass and high mass star formation. Preliminary indications from a *Hubble Space Telescope* search for planetary transits in the globular cluster 47 Tucanae (Gilliland et al. 2000; Brown et al. 2000), in which the fraction of giant short-period planets appears to be at least an order of magnitude below the value in the solar neighbourhood (Marcy & Butler 2000), are consistent with this conclusion (provided, of course, that we assume that planet-bearing stars in the solar neighbourhood were *not* themselves formed within rich clusters). With hindsight, however, numerous plausible explanations for the deficit of planets in this dense, low metallicity system are likely to be forthcoming (see e.g. Bonnell et al. 2000).

2. Disc lifetime in stellar clusters

2.1. Ultraviolet flux

Theoretical estimates suggest that there is no reason why protoplanetary discs around isolated low mass stars should not survive for lengthy periods, especially if the rate of angular momentum transport (and hence accretion) within the disc is reduced due to the low ionization fraction at a few AU (Matsumoto & Tajima 1995; Gammie 1996; Armitage, Livio & Pringle 2000). Although estimates of the ages of pre-main-sequence stars are subject to significant uncertainties (Tout, Livio & Bonnell 1999), some low mass stars ($M \approx 0.5 M_\odot$) do appear to retain their discs for more than 10 Myr (Strom 1995; Brandner et al. 2000). The disc lifetime is found to be much shorter for more massive stars (Strom 1995), and this, coupled with the observation of substantial mass loss rates from discs in the Orion Nebula (McCullough et al. 1995; Johnstone, Hollenbach &

Bally 1998; and references therein), suggests that photo-evaporation of the discs is an important process that can lead to their destruction (for a review see e.g. Hollenbach, Yorke & Johnstone 2000)

Photoevaporation of discs has been extensively studied, both when the source of ionizing radiation is the central star (Shu, Johnstone & Hollenbach 1993; Hollenbach et al. 1994), and for the case relevant here where the radiation field arises externally (Johnstone, Hollenbach & Bally 1998; Störzer & Hollenbach 1999). In the simplest analysis, ultraviolet radiation heats the disc surface, raising the sound speed to c_s. Beyond a radius,

$$R_g \approx 0.5 \frac{GM_*}{c_s^2} \tag{1}$$

the heated gas is unbound and flows away as a thermal wind. Both Lyman continuum EUV photons ($\lambda <$ 91.2 nm, $h\nu >$ 13.6 eV), and less energetic far-ultraviolet (FUV) radiation (6 eV $< h\nu <$ 13.6 eV) can contribute to disc mass loss. However, for $M_* \approx M_\odot$, FUV-driven flows (for which the sound speed in the heated layer is $\sim$ 3kms^{-1}, as compared to $\sim$ 10kms^{-1} for EUV-driven flows) have R_g that is substantially larger than the radii of principal interest for planet formation. In this paper we therefore concentrate on EUV-driven mass loss, while noting that the effects of FUV radiation will also be important for lower mass stars.

To estimate the strength of ultraviolet radiation in clusters of varying richness, we first need the emission from an individual star. For stars with 0.8 $M_\odot < M_* <$ 120 $M_\odot$, we obtain the luminosity and effective temperature T_e from stellar models computed by Schaller et al. (1992) for a metallicity $Z = 0.02$ (for these purposes, differences in metallicity are of secondary importance). We use the model output closest to $t = 10^6$ yr, which should be appropriate for young clusters of any age given the very short pre-main-sequence phase of the massive stars that dominate the UV flux. The model output is then combined with theoretical stellar atmosphere models by Kurucz (e.g. Buser & Kurucz 1992) to yield the EUV and FUV output as a function of stellar mass.

Fig. 1 shows the EUV and FUV luminosity as a function of stellar mass. A negligible fraction of the total flux is emitted in the EUV by stars with $T_e < 2.5 \times 10^4$ K, which corresponds to a mass $M_* \approx 12 M_\odot$. The fraction of flux in the EUV band then rises roughly linearly with increasing T_e to ~ 0.6 of the total for $M_* \sim 10^2 M_\odot$ stars with $T_e \approx 5 \times 10^4$ K. Significant fluxes of FUV radiation are produced by lower mass stars with $T_e > 10^4$ K.

For a standard mass function the most massive stars are rare. Fig. 1 also shows which stars dominate the output of EUV and FUV radiation in a cluster. We assume a Kroupa, Tout & Gilmore (1990) mass function for $M_* <$ 1 $M_\odot$, and a Salpeter (1955) form, $n(M)dM \propto M^{-2.35}$, for higher masses. Both the FUV and (especially) the EUV flux is expected to be dominated by the most massive star in a cluster.

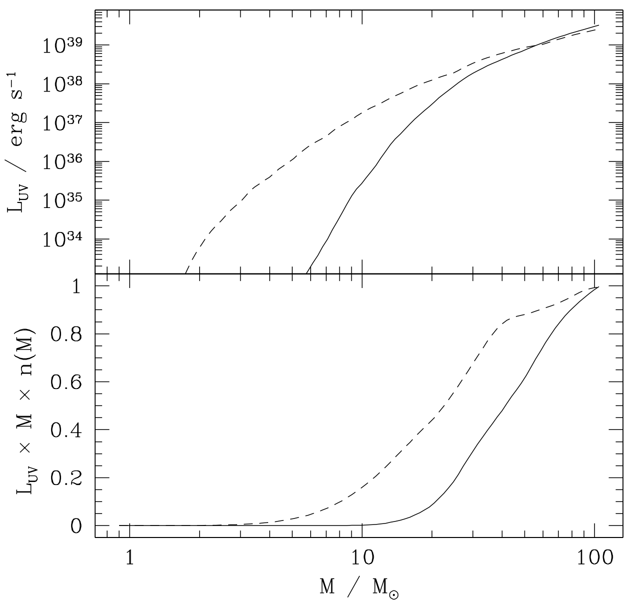

Fig. 1. Upper panel, the luminosity in EUV (solid lines) and FUV (dashed lines) for stars of mass M_*. The lower panel shows, for a Salpeter mass function, the expected relative contribution to the total flux from stars of different masses. The units in the lower panel are arbitrary.

Using this mass function, with a low mass cutoff at 0.1 $M_\odot$, and a high mass cutoff at 120 $M_\odot$, we generated realizations of clusters with number of members $n_{\rm cluster}$ ranging from 10 to 10^5. Fig. 2 shows the resultant integrated EUV luminosities. The median luminosity rises steeply for smaller clusters, which do not fully sample the high mass end of the mass function, and becomes linear only for larger clusters with $n_{\rm cluster} > 10^3$. The dependence of the luminosity on the single most massive star that a cluster happens to have implies a large dispersion in the integrated luminosity. The range of luminosities that encompasses 90% of the probability distribution spans almost 3 orders of magnitude at $n_{\rm cluster} = 10^3$, and is still a factor of ~ 3 at $n_{\rm cluster} = 10^4$. This implies that otherwise similar clusters in which the maximum stellar mass varies can have widely different UV environments, leading to substantial dispersion in the predicted lifetimes of circumstellar discs.

2.2. Disc lifetime

The theory of EUV-driven flows from discs provides a prediction for how the mass loss rate scales with the flux of ionizing photons. In the simplest analysis, the mass loss rate for a disc of fixed radius, at distance d from a source emitting a flux of ionizing photons Φ, scales as (Bertoldi & McKee 1990; Johnstone, Hollenbach & Bally 1998),

$$\dot{M}_{\rm outflow} \propto \Phi^{1/2} d^{-1}. \tag{2}$$

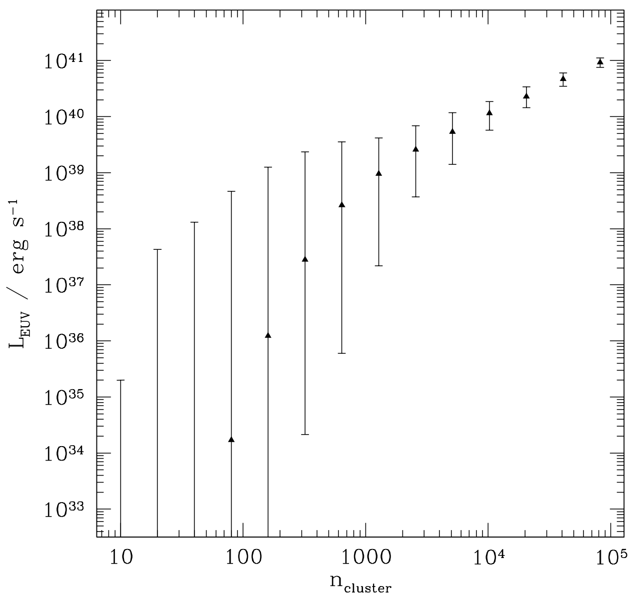

Fig. 2. The integrated EUV luminosity for clusters with $n_{\rm cluster}$ stars. The points show median values, the error bars show the range that encloses 90% of the distribution of luminosities.

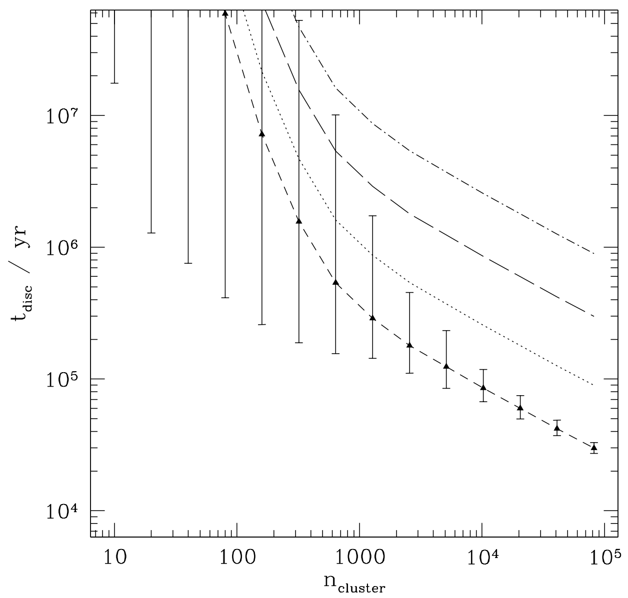

Fig. 3. The predicted dependence of the disc lifetime on cluster size, for discs at different radii, 0.1 pc (lower dashed line), 0.3 pc (dotted line), 1 pc (long dashed line), and 3 pc (dot-dashed line). The error bars plotted for the 0.1 pc curve show the range of predictions that include 90% of the probability distribution. Errors on the other curves are identical.

More sophisticated analysis are available (Störzer & Hollenbach 1999; Richling & Yorke 1998), but are hardly warranted here given the uncertainties.

To calibrate the predicted disc lifetime, we make use of the results obtained in Orion. The most massive star in the Orion Trapezium, θ^1 Ori C, has a mass estimated at around $40 - 50\ M_\odot$ (Hillenbrand 1997). Both this mass, and the estimated ionizing flux in Orion of the order of $\Phi \sim 10^{49}\ {\rm s}^{-1}$, fall withing the range expected for clusters with $n \sim 10^3$. Within Orion, one of the best studied evaporating discs, HST 182–413, at a projected distance of 0.12 pc from θ^1 Ori C, has an estimated mass loss rate $\dot{M}_{\rm outflow} = 4.1 \times 10^{-7}\ M_\odot {\rm yr}^{-1}$. The disc radius $r_{\rm disc}$ is ≈ 100 AU, and the estimated disc mass $0.04\ M_\odot$ (Johnstone, Hollenbach & Bally 1998). This disc mass is consistent with the upper end of the distribution of disc masses inferred from mm-wavelength observations by Osterloh & Beckwith (1995). For this object, the characteristic disc lifetime is therefore $t_{\rm disc} \equiv M_{\rm initial} / \dot{M}_{\rm outflow} \approx 10^5$ yr.

For planet formation, we are interested in smaller discs than that which presently surrounds HST 182–413. These will have smaller mass loss rates, which in the case of EUV-dominated flows scale as $r_{\rm disc}^{3/2}$ (Johnstone, Hollenbach & Bally 1998). Scaling to a solar system sized disc (30 AU), and assuming conservatively that the mass remains similar to that of HST 182–413, we obtain $t_{\rm disc} \simeq 6 \times 10^5$ yr as a simple estimator of the disc survival time for $\Phi = 10^{49}\ {\rm s}^{-1}$ and $d = 0.12$ pc. This estimate of the time available for planet formation before the disc is destroyed is certainly crude, and in particular ignores completely the effects of angular momentum transport in the disc. However, viscosity will tend to *hasten* disc destruction by moving material to larger radii where it can be lost via photoevaporation more easily.

Fig. 3 shows the dependence of the predicted disc lifetime on the size of the cluster, for discs located at distances d from the principal source of ionizing radiation. For smaller clusters this will typically be a single massive star, while for rich clusters with $n_{\rm cluster} \sim 10^4$ or larger several stars will contribute. We assume that, as in Orion, these stars are formed near the cluster centre (Bonnell & Davies 1998), and thus can be treated as a single radiation source. If in reality the massive stars were instead distributed throughout the cluster, that would result in a *larger* volume over which significant ablation of discs would occur. Similarly, mixing of the cluster over timescales shorter than the disc lifetime increases the fraction of stars whose discs are affected by photoevaporation.

By construction, the dependence shown in Fig. 3 is consistent with a destruction timescale of a few $\times 10^5$ yr in the inner (~ 0.1 pc) part of Orion near θ^1 Ori C. It is also consistent with observed disc lifetimes of a few Myr, extending upwards to more than 10^7 yr, in poor clusters with just a few hundred members. A large dispersion in disc lifetime is expected in this case.

For clusters richer than Orion, the volume over which photoevaporation significantly curtails the disc lifetime grows. For large $n_{\rm cluster}$, $\Phi \propto n_{\rm cluster}$, and the volume within which mass loss is significant scales as $n_{\rm cluster}^{3/2}$. Thus, for rich clusters, a larger fraction of the discs will be ablated by the action of the radiation field, even if the central cluster density remains constant. For $n_{\rm cluster} = 10^5$, the disc lifetime is expected to be severely curtailed (less than a few $\times 10^5$ yr) out to distances of the order of 1 pc, and to be significantly reduced (to $< 10^6$ yr, an order of magnitude below the value inferred for isolated discs), out to distances of perhaps $3 - 5$ pc.

2.3. Planet formation

In the Solar System, the observation that the gas fraction of the outer planets varies substantially has been taken to imply that these planets formed at roughly the epoch when the gas disc was being dissipated, probably at about a few $\times 10^6 - 10^7$ yr (e.g. Shu, Johnstone & Hollenbach 1993; Störzer & Hollenbach 1999). A few Myr is also the typical theoretical estimate for the time required for a growing core at 5 AU to reach a mass where it can rapidly accrete gas from the disc in a runaway manner (Pollack et al. 1996). Somewhat shorter timescales are derived if the cores initially migrate inwards through the gas disc, but subsequently halt and accrete the gas at smaller radii (Papaloizou & Terquem 1999). These timescales suggest that a disc lifetime of 10^6 yr might well pose difficulties for giant planet formation, at least in some theoretical models, while lifetimes closer to 10^5 yr would very probably preclude giant planet formation. From Fig. 3, this suggests that giant planet formation will be strongly suppressed in clusters with $\sim 10^5$ stars out to around 1 pc, and possibly at substantially larger radii. We also note that since short period planets (analagous to that orbiting 51 Peg) are unlikely to have been formed *in situ* (Bodenheimer, Hubickyj & Lissauer 2000), the disc must survive for a significant additional time, subsequent to planet formation, to allow inward migration through the gas disc (Lin, Bodenheimer & Richardson 1996). Some additional reduction in the frequency of such systems would then result. Low mass planets are largely unaffected by these considerations. Indeed, since rapid inward migration through the disc can substantially deplete the population of such objects (e.g. Ward 1997, and references therein), the rapid removal of the gas could in principle even enhance the initial frequency of low mass planets in clusters.

The conclusion that rapid disc destruction in clusters severely reduces the probability of planet formation can be evaded in two ways. First, massive planets might form from the disc via direct hydrodynamic collapse (e.g. Boss 1998, 2000; Cameron 1978). If this process occurs at all, it is most likely at very early times when the disc is massive and vulnerable to gravitational instability. A detection of massive planets around systems where the disc lifetime was very short would constitute indirect but persuasive evidence for the importance of this process. Second, if there is a significant delay between the epoch of low mass and high mass star formation, planets could have time to form before the discs began to be exposed to ionizing radiation. In Orion, observations suggest that at least some low mass star formation appears to have been underway well before the formation of the high mass members of the cluster (Palla & Stahler 1999), while in some theoretical models for high mass star formation prior low mass star formation is a necessary ingredient (Bonnell, Bate & Zinnecker 1998). More generally, unless star formation in a cluster is somehow synchronized to better than the sound crossing time of the gas in the star forming region, there is bound to be some spread in the times at which stars form. Since high mass stars are relatively scarce, this would typically lead to some low mass stars in the cluster forming well before the first massive star turns on and begins the process of disc destruction.

3. Discussion

As searches for extrasolar planets extend beyond the immediate solar neighbourhood, it will become possible to study how the frequency and properties of extrasolar planetary systems depend upon the star formation environment. In this paper, I have argued that in what may be the typical setting for star formation (Clarke, Bonnell & Hillenbrand 2000) – a cluster containing a mix of high and low mass stars – photoevaporation of protoplanetary discs severely limits the time available for giant planet formation. Observations indicate that discs are being rapidly destroyed by this process within a few tenths of a pc of Orion's Trapezium, and the effect will be stronger in richer clusters. For a cluster of 10^5 stars, the disc lifetime is likely to be significantly reduced when compared to that of discs around isolated stars, out to a distance from the cluster centre of several pc. Unless planets form contemporaneously with the disc itself (Boss 1998), or there is a significant delay (perhaps 10^6 yr or more) between the epochs of low mass and high mass star formation, the fraction of stars in rich clusters with massive planets is likely to be small. This provides both a possible explanation for the apparent dearth of massive, short-period planets in 47 Tucanae (Gilliland et al. 2000; Brown et al. 2000), and suggests that planet formation could also be noticeably suppressed in substantially less dense clustered environments.

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