Destruction of protoplanetary disks in the Orion Nebula Cluster

Aylwyn Scally and Cathie Clarke

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England

ABSTRACT

We use numerical N-body simulations of the Orion Nebula Cluster (ONC) to investigate the destruction of protoplanetary disks by close stellar encounters and UV radiation from massive stars. The simulations model a cluster of 4000 stars, and we consider separately cases in which the disks have fixed radii of 100 AU and 10 AU. In the former case, depending on a star’s position and orbit in the cluster over 10⁷ years, UV photoevaporation removes at least 0.01 M⊙ from its disk, and can remove up to 1 M⊙. We find no dynamical models of the ONC consistent with the suggestion of Störzer and Hollenbach (1999) that the observed distribution and abundance of protostars could be explained by a population of stars on radial orbits which spend relatively little time near θ¹C Ori (the most massive star in the ONC). Instead the observations require either massive disks (e.g. a typical initial disk mass of 0.4 M⊙) or a very recent birth for θ¹C Ori. When we consider the photoevaporation of the inner 10 AU of disks in the ONC, we find that planet formation would be hardly affected. Outside that region, planets would be prevented from forming in about half the systems, unless either the initial disk masses were very high (e.g. 0.4 M⊙) or they formed quickly (in less than ~ 2 Myr) and θ¹C Ori has only very recently appeared.

We also present statistics on the distribution of minimum stellar encounter separations. This peaks at 1000 AU, with only about 4 per cent of stars having had an encounter closer than 100 AU at the cluster’s present age, and less than 10 per cent after 10⁷ years. We conclude that stellar encounters are unlikely to play a significant role in destroying protoplanetary disks. In the absence of any disruption mechanism other than those considered here, we would thus predict planetary systems like our own to be common amongst stars forming in ONC-like environments.

Also, although almost all stars will have experienced an encounter at the radius of the Oort cloud in our own system, this only places a firm constraint on the possible birthplace of the Sun if the Oort cloud formed in situ, rather than through the secular ejection of matter from the planetary zone.

Key words: planetary systems – Solar system: formation – open clusters and associations: individual: Orion Nebula Cluster – celestial mechanics, stellar dynamics – accretion, accretion disks

1 INTRODUCTION

The formation of planets from the gas and dust around a young star is thought to take several million years (e.g. Lis- sauer (1993), Pollack et al. (1996)). During this time, the star is unlikely to move far from the region where it itself was formed, and its early evolution will continue to be influenced by the conditions there. Such regions may vary considerably, but the dominant environment for Galactic star formation is one containing thousands of young stars in a cluster of high density (typically 10⁴ stars pc⁻³), and in which the spectrum of stellar masses extends to bright O and B type stars – from which they are usually known as OB associations (Miller & Scalo 1978; Clarke, Bonnell & Hillenbrand 2000). The presence of these many other stars may have serious implications for the nascent planetary system, as close stellar encounters can tidally disrupt the protoplanetary disk, and UV radiation from the massive stars can destroy it through photoevaporation.

The Orion Nebula Cluster (ONC), a nearby star-forming region only a few million years old, is just such an environment. Containing over 4000 stars within a volume five parsecs across, it nestles at the edge of the giant molecular cloud in Orion, about 470 pc away, and its spectacular
appearance has made it a familiar astronomical image. At its centre are the four bright Trapezium stars, of which the most massive, θ1 C Ori, is by far the dominant source of UV radiation in the cluster.

There is evidence to suggest that the majority of stars in the ONC have circumstellar disks. Over 40 have now been observed directly with the Hubble Space Telescope, either silhouetted against the background nebula or embedded inside a bright ionized envelope of matter (a proplyd) (McCaughrean & O’Dell 1999; O’Dell & Wong 1999; Bally O’Dell & McCaughrean 2000). The existence of many more can be inferred from an excess in the near infrared continuum emission from stars in the cluster. Measurements by Hillenbrand et al. (1998) found evidence for disks around 55–90 per cent of their sample of ~1600 stars, and more recently, Lada et al. (in press) have narrowed this fraction to 80–85 per cent in their observations.

In this paper we present the results of N-body simulations of the ONC using Aarseth’s \texttt{nbody6} code (Aarseth 2003), and their implications for disk destruction by photoevaporation and stellar encounters. Such an approach is necessary to properly calculate the effects of photoevaporation, because the mass loss rate from a disk due to an incident UV flux is determined by its distance from the flux source. The model we use for this, due to Johnstone, Hollenbach & Bally (1998), Störzer & Hollenbach (1999) and references in Hollenbach, Yorke & Johnstone (2000), is in agreement with measurements made by Henney & O’Dell (1999), who found mass loss rates of ~ 4 × 10⁻⁷ M⊙ yr⁻¹ from proplyds close to θ1 C Ori. If these objects have spent the whole age of the ONC in this environment, their initial masses must have been greater than 0.8 M⊙, and we might expect to see some disks today with a non-negligible fraction of this mass present. However mm-wavelength observations of disks in the ONC indicate (Lada et al. 1998; Bally et al. 1998) disk masses no greater than 0.02 M⊙. The paradox might be resolved if θ1 C Ori was born only very recently – at most 5 × 10⁴ yr ago – or if the dynamics of the ONC were such that the proplyds seen close to θ1 C Ori today have spent most of their lives elsewhere in the cluster, as has been suggested by Störzer & Hollenbach (1999). We investigate this possibility in simulations in which the cluster undergoes a collapse from cold initial conditions.

The relevance of cluster dynamics for the destruction of disks by stellar encounters is even more readily apparent. A full dynamical simulation is necessary to improve on analytic approximations in which stars remain in the same density environment throughout the life of the cluster (e.g. Clarke & Pringle 1993). Until recently however, N-body codes suppressed strongly gravitationally focused encounters by smoothing the gravitational field on small scales. In the ONC, typical encounters are gravitationally focused at impact parameters less than 160 AU, so a proper evaluation of systems on the scale of interest for planet formation could not be made with such codes. In this work we use \texttt{nbody6}, which represents the state of the art in dynamical simulation on a commercial hardware platform, and which incorporates two-body regularisation algorithms to handle close encounters without smoothing.

2 COMPOSITION AND DYNAMICS OF THE ONC

Although the ONC is relatively close, the large amounts of gas and dust present and the bright emission from the Trapezium stars have until recently hidden much of its population, and prevented us from accurately measuring its kinematics. In the past decade, however, deep and high resolution studies at optical wavelengths (Prosser et al. 1994) and adaptive optical techniques in the infrared (McCaughrean & Stauffer 1994) have greatly improved our understanding of the cluster’s size and composition.

Hillenbrand & Hartmann (1998) detected 3500 stars down to mass 0.1 M⊙ within 2.5 pc of the cluster centre. A subsequent survey of the central 0.7 × 0.7 pc² (Hillenbrand & Carpenter 2000) down to mass 0.02 M⊙ found an additional 20 per cent stars in that region. The overall mass spectrum was found to be similar to that of the Galactic field. In this work we therefore consider a population of 4000 stars, with a mean mass of around 0.5 M⊙ – though the true population is probably higher still.

Jones & Walker (1988) measured a (three-dimensional) velocity dispersion $\sigma = 4.3 \pm 0.5$ km s⁻¹ for about 1000 stars distributed within 2 pc of the centre. Combined with a half-mass radius $R_h = 1$ pc, this gives a crossing time $T_c = 2R_h/\sigma \approx 0.5$ Myr. The age of the cluster is difficult to determine, but data from Hillenbrand (1997) and Hillenbrand & Carpenter (2000) suggest that perhaps 85 per cent of its stars are less than 2 Myr old (with a mean age of ~ 0.8 Myr). The cluster thus seems to be dynamically young – a few crossing times old.

Using these parameters, a rough calculation of the virial ratio (kinetic energy / potential energy) of the cluster gives a value of about 1.5. Some authors have concluded from this that either the ONC must be unbound and expanding, or there must be a significant amount of gas or stars – perhaps low-mass binary companions – present and not seen. Jones & Walker (1988; Tian et al. 1996; Hillenbrand & Hartmann 1998; Kroupa 2000). However, reasonable errors in the observational parameters can easily account for an error of over 50 per cent in this calculation. The density profile of the cluster is very much that of a relaxed system, to the extent that Hillenbrand & Hartmann (1998) were able to fit a King model – characteristic of globular clusters many relaxation times old – to their data.

In addition, we note that even if the ONC is unbound today, it is unlikely to have been so over much of its past evolution. A highly unbound cluster will always appear only ~ 4 M⊙ – though the true population is probably higher still.

* There are, however, many uncertainties involved in these estimates. See Henney & O’Dell (1999).

† Note that the asymptotic density distribution of a highly unbound cluster is simply mapped from its initial velocity distribution, since ultimately $r \approx vt$ for each star. Thus an initial velocity...
3 PROPLYDS AND PHOTOEVAPORATION

About 150 young stellar objects in the ONC have been observed with the central star and disk surrounded by a bright extended ionisation front, and a tail streaming in the direction away from a nearby massive star – usually θ¹ Ori. These objects are known as proplyds (after O’Dell, Wen & Hu (1993), and in recent observations (Bally, O’Dell & McCaughrean 2000) about 80 per cent of the objects within 0.14 pc of the Trapezium stars are of this type. The fraction seems to rise as one looks closer to the cluster centre (O’Dell & Wong 1996), though this may be merely a selection effect, since their brightness drops in proportion to the square of their distance from θ¹ Ori, while the background nebula fades less rapidly (O’Dell, personal communication).

A model for these objects has been developed by Johnstone, Hollenbach & Bally (1999) and Störzer & Hollenbach (1999) (see Hollenbach, Yorke & Johnstone (2000) for a review), in which their structure and mass loss rate at a given distance from a massive star is determined by the relative strengths of the star’s far ultraviolet (hν < 13.6 eV, hereafter FUV) and extreme ultraviolet (hν > 13.6 eV, hereafter EUV) fluxes at that point. Specifically, they propose that there are two regimes in which photoevaporation operates. In the inner one, FUV photons dominate the mass loss by heating the circumstellar disk and causing a neutral flow out to an ionisation front, where it meets the EUV field, as seen in the proplyds. Within this regime the model predicts a mass loss rate roughly independent of the distance d from the massive star, since the only criterion for it to apply is that the FUV flux is sufficiently strong to heat the disk matter above its escape velocity. In the EUV regime, there is no neutral flow and the mass loss rate depends directly on the square of their distance from θ¹ Ori, while the background nebula fades less rapidly (O’Dell, personal communication).

Using the same physical parameters as were assumed by Störzer & Hollenbach (1999), Hollenbach, Yorke & Johnstone (2000) give the following expressions for the mass lost by a disk in the FUV and EUV dominated regions:

\[ M_{\text{FUV}} \approx 2 \times 10^{-9} r_d M_\odot \text{yr}^{-1} \]  
\[ M_{\text{EUV}} \approx 8 \times 10^{-12} r_d^{3/2} \sqrt{\frac{\Phi_1}{c^2}} M_\odot \text{yr}^{-1} \]  

where \( r_d \) is the disk radius in AU, \( \Phi_1 \) is the ionising (EUV) photon luminosity of the massive star in units of 10^{38} s^{-1}, d is its distance in pc, and we assume a column density of 5 x 10^25 cm^{-2} from the ionisation front to the disk inside a proplyd.

For θ¹ C Ori, of type O6 (Hillenbrand 1997), \( \Phi_1 = 2.6 \), and the boundary between the EUV and FUV dominated regions stands about 0.3 pc from the star (Störzer & Hollenbach 1999). The great majority of proplyds in the ONC have indeed been observed within this distance, and it may be that those few outside (∼ 10 per cent in the survey of O’Dell & Wong (1996)) involve a wind production mechanism other than FUV heating. The other bright stars in the cluster are all less massive and have significantly less UV output, with \( \Phi_1 \approx 0.2 \) for the second most massive (type O9), and \( \Phi_1 \approx 0.05 \) for the third (type B0). Their FUV-dominated regions will be correspondingly smaller (∼ 0.1 pc and 0.05 pc respectively), as will their photoevaporative effects.

The effect on planet formation is complicated by the fact that there is a lower limit on the size to which disks can be reduced by the photoevaporation process. Ultimately this is determined by the mass of the star, since for matter to escape from the disk at any point it must be heated above the local escape velocity, corresponding to the limit

\[ r_{\text{min}} \approx \frac{GM_*}{2c^2} \]  

where \( M_* \) is the stellar mass and \( c_s \) is the sound speed in the heated flow. For a 0.3 M_⊙ star (corresponding roughly to the mode of the mass distribution in the ONC), the minimum radius in the FUV-dominated region will be about 15 AU, while in the EUV-dominated region evaporation can continue down to 1–2 AU – the difference being a consequence of the differing sound speeds in EUV and FUV heated flows (10 km s^{-1} and 3 km s^{-1} respectively) (Johnstone, Hollenbach & Bally 1998). Even in an FUV-dominated region, once the disk becomes too small for FUV radiation to drive a neutral flow, EUV-dominated mass loss will set in for that system.

Within the minimum radius, planets may well be able to form without hindrance, and for most systems we may expect photoevaporation to have very little effect on planets forming at about 5–10 AU from their central star (and none whatsoever on planets in the inner 1 AU). But this central zone is exactly the region we are most interested in for planet formation: the planets in the Solar System are found there, as are many of the close gas giants that have been discovered recently around nearby stars.

4 SIMULATIONS

We construct a dynamical model of the ONC, implemented using Aarseth’s nbody6 code (Aarseth 2003), consisting of 4000 stars, and starting from a density distribution going as \( r^{-2} \). Except where stated otherwise (in the discussion of Figure 3), the results shown refer to a cluster in virial equilibrium with a half-mass radius of \( ∼ 1 \) pc, and in all cases the initial conditions are chosen to match the appearance of the ONC after an evolution time of 2–3 Myr (a few crossing times). The mass function used is that of Kroupa, Tout & Gilmore (1993), and the three most massive stars are assigned the UV flux parameters specified in the previous section (\( \Phi_1 = 2.6, 0.2 \) and 0.05). Of these, the most massive is placed at the cluster centre, while the other two are given random initial locations. Several random realisations of this setup were generated and run, but no statistically significant variations were found, and the results presented here for one particular model are characteristic of all those generated.

\[ \text{‡} \] The additional factor of \( ∼ 0.5 \) is due to the fact that material can actually escape from inside \( GM_*/c_s^2 \) (Johnstone, Hollenbach & Bally 1998).
To model photoevaporation, we run two series of simulations. In the first we are interested in the distribution of proplyds (in the FUV-dominated region) and for every star in the cluster, so we keep track of three things during the course of the simulation:

- the cumulative time it spends in the FUV-dominated region of any UV source.
- the time-integrated value of \( \sqrt{\Phi_i/d^2} \) for all three UV sources whenever it is outside an FUV-dominated region.
- the closest approach \( r_{\text{close}} \) it makes to any other star.

We then use the first two of these in (1) and (2) to evaluate the total mass lost by each star due to photoevaporation during its life in the cluster by assuming a fixed disk radius for all the systems throughout - which we take to be 100 AU.

The assumption that the disk radii remain fixed throughout is a simplification, since in reality it is likely that the disks will decrease in size as they lose mass through evaporation. This would in turn lead to a reduction in the mass loss rate, which scales with the disk radius \( r_d \) in both the EUV and FUV regimes, as shown in (1) and (2). Johnstone, Hollenbach & Bally (1998) calculate the implied variation with time \( t \) (at a fixed distance from the ionising star) as \( r_d \propto t^{-1} \) (EUV) and \( r_d \propto t^{-2} \) (FUV) for a disk whose surface density goes as \( r^{-3/2} \), and assuming that the disk is unable to replenish the outer regions from which material evaporates.

Direct measurements of disk radii are difficult to make, and to a certain extent depend on the wavelength one observes at. However, estimates for various proplyds in the ONC (Johnstone, Hollenbach & Bally 1998) vary from 20 to 80 AU, and are in agreement with the model’s predictions taking into account the size of the ionisation front stand-off and the distance to \( \theta^1 \)C Ori in each case (Störzer & Hollenbach 1999). Given this, and the possibility that the disks might have been much larger in the past if they have already suffered a long period of photoevaporation, we take a fixed value of 100 AU for these objects as a simplifying assumption which will underestimate the total mass evaporated to date. It would of course be possible to repeat our calculations while also keeping track of the disk size for each system, but this would necessitate making an assumption about their initial size – as well as incorporating the assumption that there is no viscous replenishment of the outer disk. This would seem to be unwarranted in the light of our finding (later in this section) that the mass loss assumption already implies unacceptably large initial disk massees for the proplyds.

In the second series of simulations we are interested in mass loss from the planet-forming region of the disk, i.e. the inner \( \sim 10 \) AU. We assume that there is no FUV-driven mass loss from this region – which is true for any star more massive than \( \sim 0.2 \) \( M_\odot \) (more than 60 per cent of cluster stars) – so that for each star we only need to keep track of the time-integrated value of \( \sqrt{\Phi_i/d^2} \) for all three UV sources. This is converted to a mass loss in (2) by setting \( r_d = 10 \) AU. Once again the fixed disk radius assumption is a simplification, which in this case will overestimate the mass loss from the disk region we are interested in. (We assume that the existence of disk material at radii greater than 10 AU does not increase the mass loss rate within that radius.)

Figure 1 shows a histogram of mass loss due to photoevaporation after 2.89 Myr (roughly the ONC’s current age) in the case where the disks are 100 AU in radius. We see that almost all systems have lost more than 0.01 \( M_\odot \), and that the rightmost bin contains systems which have spent their whole time in \( \theta^1 \)C Ori’s FUV-dominated region.

Figure 2 shows, at various times during the life of \( \theta^1 \)C Ori, the percentage of stars in the central projected 0.15 pc of the cluster which are proplyds, as a function of the initial disk mass (assuming all disks are equal initially). A proplyd in this context is a star in an FUV-dominated region with some circumstellar disk matter remaining (and recall that the radius of \( \theta^1 \)C Ori’s FUV-dominated region is 0.3 pc). At the start of the simulation (or immediately after the massive stars formed if that were different), all stars in the central 0.3 pc (in 3D) would be proplyds, corresponding to \( \sim 80 \) per cent of the stars within 0.15 pc in projection, given the ONC’s density distribution. But low mass disks are very quickly destroyed, and to match the observed distribution of proplyds at the ONC’s present age requires a high initial disk mass (0.4–0.6 \( M_\odot \) in Figure 2) for these stars. (Note that these initial disc masses would have to be even higher if we were to include the effect of evaporation reducing the disk radii and mass loss rates.)

Figure 3 is a similar plot showing data from a model starting in an initially cold configuration, with potential energy much greater than its kinetic energy. Such a system undergoes an initial collapse, after which it virialises at about half its initial size (subject to some continuing small oscillation in radius). The period of maximum density in the collapse is called the “crunch”, and models which have just passed through it can look similar to the ONC. The initial density profile is important however, and models starting from an \( r^{-2} \) profile provide a better match to the ONC at its present age than those starting from uniformity. In the
Figure 2. Variation with initial disk mass of the percentage of stars inside 0.15 pc (in projection) which are proplyds (i.e. in an FUV-dominated region with some circumstellar disk matter remaining) after 0.96, 1.9, 2.9, 3.9, and 4.8 Myr. All disks are assumed equal in mass initially and have fixed radii of 100 AU. At 4.8 Myr the percentage has dropped dramatically because we assume θ¹C Ori leaves the main sequence at 4.6 Myr, after which only one or two less massive (but longer lived) stars remain to ionize any disks.

latter case, the core tends to be underdense, to the extent that only about half the stars appearing in the central 0.15 pc in projection are within 0.3 pc in 3D. Such a model can therefore never match the observations, in which 50 per cent of stars in the centre are proplyds. The plot shown here is for a cluster after 2.8 Myr with an initial r−2 density profile. It seems that the dynamics have made little difference to how the fraction of proplyds varies with initial disk mass, when compared to the case of virial equilibrium. Stars which fall into θ¹C Ori’s FUV-dominated region during the collapse tend to stay there, and so for low-mass disks, the population of depleted disks builds up even as new proplyds appear.

Note also that as time progresses, for any reasonable cluster dynamics, the distribution of proplyds around θ¹C Ori should deplete from the inside out, as these stars are more likely to have spent more time in the FUV-dominated region. This assumes, of course, that there is no other significant mechanism for creating proplyds, and that accretion does not replenish the disks.

Figure 3. As Figure 2 but for an initially cold cluster after 2.8 Myr.

decrease in the incidence of disks revealed by near infrared excess.

4.2 Encounters

Figure 4 shows histograms of r_close for all the stars in the cluster at the ONC’s present age and at 12.5 Myr. In this particular run we find that only about 3 per cent of stars have had an encounter 100 AU or closer at the present age, rising to 6 per cent after 12.5 Myr. Typical values for these fractions, averaged over a number of different runs, are ~ 4 per cent and 8 per cent respectively.

Figure 5 shows histograms of r_close against radial position, both in projection and in three dimensions, at the ONC’s present age. On the plot in projection, we see no trend with R_{proj} outside 1 pc from the cluster centre, with almost all stars having a value of r_close between 10³ and 10⁴ AU, even though the stellar density drops by more than an order of magnitude over the range plotted.

It is interesting to compare this with what one would expect if each star had spent its whole time at the radius observed today – i.e. if no orbit in the cluster had any significant radial component. To make this comparison, we perform a Monte Carlo data simulation, the details of which are presented in the Appendix. In outline, the simulation considers stars in radial bins, each bin having a local density which determines the rate of encounters within any given distance. Encounters are generated and assigned to the stars in the bin at random, and we take the closest encounter for each star after the required time (2.89 Myr in this case, to compare with the dynamical simulation). This gives a distribution in r_close for each radial bin; Figure 6 plots its median and its 2σ and 3σ limits against the data from nbody6.

The Monte Carlo simulation matches the dynamical data remarkably well, with the median, in particular, providing a good fit to the ‘centre’ of the distribution of stars. Its
outer limits in $r_{\text{close}}$ are narrower, and this may reflect the influence of orbital mixing in the dynamical simulation, but the effect is minor, and we conclude that simple analytical estimates give a good measure of the encounter distribution at 2–3 Myr.

We find, however, that in evolving from $10^5$ to $10^7$ years, the closest encounter distribution hardly changes. This is in marked contrast to the analytic estimates, which imply that as a result of the increase in available time the distribution should move to smaller radii. For example, Bonnell et al. (in press) find that after $10^7$ years, all of the systems in the core of a cluster like the ONC (where the stellar density is $10^4 \text{pc}^{-3}$) have had an encounter within 100 AU, whereas in our models less than one third of the systems in the core have had such a close encounter. The difference between the two is mainly due to the fact that our model clusters become significantly less dense over this timescale. This evolution is not driven by mass loss or by super-virial initial conditions (though these would have a similar effect), but is a consequence of the fact that our initial conditions do not represent a steady-state solution of the collisionless Boltzmann equation. The model clusters are generated with a sharp discontinuity at the cluster edge, where the density drops to zero. In principle, the ONC could be the centre of a much more extended distribution of stars comprising a steady state distribution, as in the King model fit of Hillenbrand & Hartmann (1998), and in such a case the density

\[ \frac{\text{two is mainly due to the fact that our model clusters become significantly less dense over this timescale. This evolution is not driven by mass loss or by super-virial initial conditions (though these would have a similar effect), but is a consequence of the fact that our initial conditions do not represent a steady-state solution of the collisionless Boltzmann equation. The model clusters are generated with a sharp discontinuity at the cluster edge, where the density drops to zero. In principle, the ONC could be the centre of a much more extended distribution of stars comprising a steady state distribution, as in the King model fit of Hillenbrand & Hartmann (1998), and in such a case the density} \]
5 DISCUSSION

5.1 Proplyds

It is clear from the mass loss rate that photoevaporation can remove a large amount of disk material from systems in the core of the ONC over the ∼ 5 Myr lifetime of θ¹C Ori. Our simulations, which keep track of the stars' varying distances from θ¹C Ori as they orbit in the cluster, allow us to quantify the fraction of systems that never spend any significant time near θ¹C Ori, and remain relatively unscathed by photoevaporation. They therefore shed some light on the much discussed problem of why proplyds are common in the core of the ONC, when the short inferred survival times of disks in this region would imply that most stars have already lost their disks and hence should not manifest proplyd activity.

One solution, proposed by Störzer and Hollenbach (1999), is that the proplyds are merely ‘visiting’ the core region on radial orbits. In this picture, stars light up as proplyds inside the cluster core, but since they have spent most of their lives at much larger radial distances, their disks can have survived for much longer. We find no evidence for such a population of stars on radial orbits in any dynamically plausible model for the ONC. In models that are in virial equilibrium, the velocity dispersion is initially isotropic, and remains approximately so, and the stars currently in the central region have spent most of their lives there. We find that in this case the observed high proplyd fraction is consistent only with initial disk masses in excess of 0.4 M⊙; for somewhat smaller initial disk masses, the proplyd distribution develops a ring shaped structure in projection, as only disks towards the edge of the FUV-dominated region (which spend some time outside it) can still exist. The lack of any observational evidence for such a central depletion in the proplyd distribution suggests that proplyds are not close to the point of exhaustion.

Perhaps more remarkably, we find that the ‘radial orbit’ solution of Störzer and Hollenbach also fails to be realised in the case where the cluster undergoes cold collapse. In such models (where the kinetic energy of the cluster is initially low, as would be the case if the stars had fragmented out of a hydrostatically supported medium) the stars begin by falling inwards on radial orbits. After about a free-fall time, they achieve a configuration of maximum compactness (the crunch) and rebound into a state of approximate virial equilibrium. At an age of about 2 Myr, the ONC would have evolved somewhat past the crunch and its orbits would be largely isotropic. In consequence, the predicted proplyd fraction is remarkably similar to the virialised case (Figure 3 compared with Figure 2).

Since we have shown that orbital dynamics cannot solve the proplyd frequency problem, we are forced to invoke the other two solutions considered by previous authors (Bally et al. 1998; Henney & O’Dell 1999). The first possibility is that the measured disk masses are vast underestimates.栖 Another dynamical factor not present in the Monte Carlo simulation is that for stars in the cluster core, many close encounters may occur within small-N groupings, rather than being distributed over the entire core population.

栖 Which would of course constitute an unstable disk for stars of Solar mass or less (see e.g. Laughlin & Bodenheimer 1994; Toomre 1964).
In order to solve the proplyd frequency problem, the initial disk mass required (0.4 $M_\odot$) would imply that 90 per cent of the stars only lose a small fraction of their disk mass to photoevaporation over the lifetime of $\theta^1$ C Ori. The second possibility (which would be compatible with the low measured disk masses) is that $\theta^1$ C Ori has formed only recently (implying incidentally that the ONC has been caught at a special moment, and that older clusters containing OB stars would not be expected to exhibit proplyd activity).

5.2 Planets

One might suppose that the high mass loss rates implied by (1) should lead to a suppression of planet formation in all populous cluster environments containing O stars, unless planets form at the same time as the disk itself. Certainly this is the case for planets forming outside the inner 10 AU of the disk, since as Figure 1 shows, even after 3 Myr most systems with 100 AU disks will have lost an amount of disk material equal to several times the minimum Solar nebula. Planets would be prevented from forming on such wide orbits in about half the systems in the ONC, unless, as discussed above, either the initial disk masses were very high (e.g. 0.4 $M_\odot$) or they formed quickly (in less than ~2 Myr) and $\theta^1$ C Ori has only very recently appeared.

However, it is the inner 10 AU where we expect most planets to be found (by analogy with our own system) and as explained in Section 2, only EUV-dominated mass loss can affect this region of the disk. Figure 1 shows that such mass loss is low – relatively few disks spend much time very close to an O star. The results indicate therefore that planet formation in the ONC would be largely unaffected by photoevaporation.

Disruption due to stellar encounters is probably also unimportant. In a star-disk encounter, matter can be stripped from the disk down to about one third of the encounter separation (Clarke & Pringle 1991), and during the lifetime of the cluster only a small minority of stars in our simulations will have had encounters close enough to affect the planet-forming region of their disks. This is essentially in agreement with the results of Bonnell et al. (in press), who find that only in the dense core of the ONC is there likely to be any noticeable disruption to young planetary systems.

Our conclusion, therefore, is that in the absence of any disk disruption mechanism other than those considered in this paper, we would predict planets in orbits within 10 AU, and perhaps planetary systems like our own, to be common amongst stars forming in ONC-like environments. As Armitage (2000) has pointed out, in much richer stellar environments, where the number of O stars is greater, photoevaporation may have a more significant impact. The observations of Gilliland et al. (in press), who find a complete absence of close (‘hot’) Jupiter-mass companions in the globular cluster 47 Tucanae (which contains more than 10^5 stars), may be an example of this. More challenging, perhaps, for our understanding of star and planet formation are the results of the gravitational lensing survey of Albrow et al. (in press), who find that less than a third of lensing stars (typically of mass ~ 0.3 $M_\odot$) have Jupiter-mass companions with orbits in the range 1.5–4 AU. If the majority of these lensing stars were formed in an environment no richer than the ONC then neither photoevaporation nor stellar encounters can explain the apparent absence of planets.

5.2.1 The Oort cloud

We note finally that all stars in the ONC should have had an encounter within a radius comparable to that of the Oort cloud in our own system (\gtrsim 20,000 AU), and that if the Oort cloud is primordial (e.g. Cameron (1973)), this could be used to rule out an origin for the Solar system in an ONC-like environment. On the other hand, it is often supposed that the Oort cloud was formed from bodies scattered out of the planet-forming zone by planetary and tidal perturbations (Oort 1950; Fernandez 1983), arriving at large radii only after about 10^7 years (Duncan, Quinn & Tremaine 1987). If the ONC is unlikely to survive as a bound cluster for that duration, its density would be considerably less by then, and an Oort type cloud might be able to survive without difficulty in the more dilute environment. Given the uncertainties in the origin of the Oort cloud, we conclude that its existence alone is not sufficient to place any firm constraints on the birthplace of the Sun.

6 ACKNOWLEDGEMENTS

We thank Matthew Bate, Sverre Aarseth, Ian Bonnell, Chris Tout, Bob O’Dell, Lynne Hillenbrand and Mark McCaughrean for valuable help and discussions. A. Scally is grateful for the support of a European Union Marie Curie Fellowship.

REFERENCES

Aarseth S. J., 2000, in Gurzadyan V. G., Ruffini R., eds, The Chaotic Universe, World Scientific
Albrow M. D. et al., in press, ApJL
Armitage P. J., 2000, A&A, 362, 908
Bally J., Testi L., Sargent A., Carlstrom J., 1998, AJ, 116, 854
Bally J., O’Dell C. R., McCaughrean M. J., 2000, AJ, 119, 219
Binney J., Tremaine S., 1987, Galactic Dynamics, Princeton University Press
Bonnell I. A., Smith K. W., Davies M. B., Horne K., in press, MNRAS.
Cameron A. G. W., 1973, Icarus, 18, 407
Clarke C. J., Bonnell I., Hillenbrand L., 2000, in Mannings V., Boss A. P., Russell S. S., eds, Protostars and Planets IV, University of Arizona Press
Clarke C. J., Pringle J. E., 1991, MNRAS, 249, 584
Clarke C. J., Pringle J. E., 1993, MNRAS, 261, 190
Duncan M., Quinn T., Tremaine S., 1987, AJ, 94, 1330
Fernandez J. A., 1985, in Carusi A., Valsecchi G. B., eds, Dynamics of comets: their origin and evolution, D. Reidel
Gilliland R. L. et al., in press, ApJL
Hayashi C., Nakazawa K., Nakagawa, Y., 1985, in Black D. C., Matthews M. S., eds, Protostars and Planets II, University of Arizona Press
Henney W. J. & O’Dell C. R., 1999, AJ, 118, 2350
Hillenbrand L. A., 1997, AJ, 113, 1733
Hillenbrand L. A. & Carpenter J. M., 2000, ApJ, 540, 236
Hillenbrand L. A. & Hartmann L. W., 1998, ApJ, 492, 540
Hillenbrand L. A., Strom S. E., Calvet N., Merrill K. M., Gatley I., Makidon R. B., Meyer M., Skrutskie M. F., 1998, AJ, 116, 1816
Appendix A: Monte Carlo Simulation of Encounters

In an environment with a given local stellar density \( n \) and one-dimensional velocity dispersion \( \sigma \), the rate of encounters (per star) closer than a given distance \( r_e \) can be calculated as

\[
f = 4\sqrt{\pi n} \left( \sigma r_e^2 + \frac{Gmr_e}{\sigma} \right)
\]

(e.g. Binney & Tremaine [1987], p. 541) where \( m \) is the stellar mass, assumed the same for all stars. In a cluster where the density \( n(r) = kr^{-2} \) for some constant \( k \) there are \( 4\pi k \delta r \) stars with radial positions in \([r, r + \delta r]\), and after a time \( T \) we expect them to have

\[
N_e(r, \delta r, r_e) = 16\pi^{3/2}k\delta r n(r)T \left( \sigma r_e^2 + \frac{Gmr_e}{\sigma} \right)
\]

encounters in total closer than \( r_e \). Normalising this to \( N_e(r, \delta r, R) \) and inverting gives a generating function for stellar encounters closer than some maximum distance \( R \):

\[
r_e = \sqrt{A^2 + BX - A}
\]

where \( X \) is a uniform random deviate in \([0, 1]\) and

\[
A = \frac{R + \frac{Gm}{2\sigma^2}}{2\sigma^2}
\]

For \( R \) we take the mean stellar separation at \( r \):

\[
R = \left( \frac{48}{\pi n(r)} \right)^{1/3}
\]

since all stars have encounters at this distance or greater at any given instant.

Our procedure is then to generate \( N_e(r, \delta r, R) \) encounters using (A3) and assign them randomly to the \( 4\pi k \delta r \) stars at radius \( r \) in the cluster. Taking the closest encounter for each star then gives a distribution of minimum encounter distances at \( r \), analogous to that obtained from the dynamical simulation (with which we match the parameters \( k, \sigma, m \) and \( T \)). Figure 3 plots the median of the distribution and its \( 2\sigma \) and \( 3\sigma \) limits.