Praesepe – two merging clusters?

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ABSTRACT
A membership catalogue for Praesepe was compiled and split into four mass bins. A contour plot indicates the presence of a subcluster some 3 pc from the centre of the cluster, of approximately 30 M⊙. A tidally truncated King profile was fitted to the remainder of the cluster and the tidal radius is found to be 12.1 pc; the mass of the cluster (excluding the subcluster) is 630 M⊙. From the calculated velocity dispersions we find that the cluster appears to have too much kinetic energy and should be rapidly disintegrating. X-ray data suggest that there may be an age spread between the main core stars and the subcluster stars. This leads us to the conclusion that Praesepe is two merging clusters.

Key words: stars: kinematics – open clusters and associations: individual: Praesepe.

1 INTRODUCTION
With the recent discovery and interest in brown dwarfs, much work has focussed on open clusters, due to the advantages that these systems present; stars in open clusters can be considered to have the same age, metallicity and distance. Many clusters are also relatively near, which further improves the prospects for the detection and investigation of brown dwarfs. However, both theory, and observational work is not as well developed for open clusters as it is for globular clusters, and it must be productive to use the increasingly comprehensive data available for open clusters for direct comparison of observation with theory.

Open clusters provide an interesting laboratory in which to compare theory with observation because of the differences between open clusters and globular clusters. Open clusters exhibit a larger mass spectrum than do globular clusters, due to their relative youth; open clusters also span a considerable range of ages, unlike the majority of globular clusters, providing the opportunity to examine the effects of some of the time-scales associated with the evolutionary process. Open clusters are closer to the earth than globular clusters, and this allows observations to be made to fainter intrinsic magnitudes than for globular clusters. As open clusters are in the galactic disc, they may encounter clouds of interstellar matter more frequently as they orbit around the galactic centre, which will impart energy to the cluster and disrupt it.

It is generally accepted that at the time of formation, stars belonging to the same cluster have approximately the same velocity. As the cluster stars move around in the cluster gravitational field they exchange energy as they encounter other cluster stars, and the system progresses towards equipartition of energy (Spitzer 1975; King 1979). This results in mass segregation, whereby the most massive stars are concentrated in the centre of the cluster, and the lower mass stars, which have greater velocities, become dispersed out to greater radii, and some may even evaporate from the cluster altogether. At the tidal radius, r, stars are subject to zero resultant gravitational force, and can be said to have escaped from the cluster.

There are three time-scales associated with this evolutionary process: the crossing time, tcr, is the average time taken for a star to cross the cluster; the relaxation time, trelx, is the time taken for the cluster stars to exchange energies and for their velocity distribution to approximate a Maxwellian equilibrium; the evaporation time, tevap, is the time taken for 63 per cent of the cluster stars to evaporate from the cluster.

The ratio of tcr to trelx is dependent upon the total number of stars in the cluster and can be defined as

\[ \frac{t_{relx}}{t_{cr}} = \frac{N}{31 \ln(N/2)} \]  

(King 1979), where N is the total number of stars in the cluster. For globular clusters, where the total number of stars is high, the crossing time is much shorter than the relaxation time, and therefore it is reasonable to assume that the velocity and density distributions are in equilibrium. For clusters with fewer stars, however, tcr may become close to, or even lower than the relaxation time, and this would then not be the case. For Praesepe, however, with approximately 1000 stars, it is reasonable to assume there is equilibrium between the velocity and density distributions.

King models seem to fit the observational data available for globular clusters well, except for a few per cent of globular clusters in which core collapse has taken place, (King 1985). Pinfield, Jameson & Hodgkin 1998 (hereafter PJH) used a King model to good effect to model the Pleiades cluster, by splitting the stars into four mass bins; this extended the comparison of theory with observation to lower mass stars than had been done before.

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Fokker–Plank modelling has been developed (Cohn 1979; Takahashi 1997), but is limited in its use for open clusters as the assumption is made that there are many small velocity changes; whilst this is reasonable for globular cluster stars, in open clusters there are far fewer stars and single encounters may result in significant changes in velocity. Even for globular clusters, however, N-body modelling is more realistic, and Portegies Zwart et al. (1997a,b, 1999) have studied globular cluster cores in this way, developing their models to include a population of primordial binaries and the effect of stellar evolution. N-body modelling of open clusters has been extended (Terlevich 1987) to take into account the effects of stellar evolution and mass loss in the cluster. Terlevich also includes the effect of tidal perturbations due to the galactic orbit, and due to tidal shocks from the passage of the cluster through interstellar clouds, as well as following the evolution of binaries. She uses a power law mass function with \( \alpha = -2.75 \) for 1000 bodies, and finds fairly good agreement between the observed distribution of galactic cluster lifetimes, and the model’s predicted lifetimes. De la Fuente Marcos (1995, 1996a,b, 1997) in his series of papers takes this even further, by examining the effect of several different initial mass functions on the dynamical evolution of open clusters. This most recent work includes the effect of mass loss due to stellar evolution and the effect of a primordial binary mass spectrum. The latter is found to affect the evolution of the cluster in an uncertain way, which depends on cluster richness and the initial mass function assumed.

In this paper, we split a membership catalogue for Praesepe into four mass bins, and fit the surface densities to a King model. Extrapolating the King model to the tidal radius allows an estimation of the total mass of the cluster. Furthermore, the best-fitting values for the core radii, \( r_c \), for each mass bin, together with the value for the central star density, allows a calculation of the velocity dispersions for each mass bin, in order that a virial analysis can be performed. This paper on Praesepe is thus similar in approach to PJH; the results, however, turn out to be very different.

2 THE OBSERVED MASS OF PRAESEPE

2.1 Compilation of the membership catalogue

The data provided by the Open Cluster Database (Prosser & Stauffer) combine data from several surveys. The Klein-Wassink survey (1927) measured proper motions out to a radius of 1″ from the cluster centre, and was followed up with photometry by a number of other authors (Johnson 1952; Crawford & Barnes 1969; Upgren, Weiss & DeLuca 1979); Artjukhina (1966a,b) completed a number of other authors (Johnson 1952; Crawford & Barnes 1969; Hambly et al. 1995) obtained proper motions and photometry for fainter stars down to \( \tanh \theta < 17 \); the survey of Jones & Stauffer (1991) obtained proper motions and photometry for fainter stars down to \( m_v = 18 \) and Hambly et al. (1995) obtained proper motions and photometry down to \( I_N = 18 \). Table 1 summarizes the sources used for this work. All proper-motion and photometric members of Praesepe were selected from this catalogue.

For the stars of greatest luminosity \( (M_v < 1.45) \), a relationship was obtained which related the bolometric corrections to absolute visual magnitude (Bohm-Vitense 1989); the bolometric magnitude and luminosity of each star could then be derived, and these were used, together with a mass-luminosity relationship (Smith 1983) to obtain masses for each star. The masses of stars in the intermediate range \( (1.45 < M_v < 10.25) \) were computed using appropriate relationships between mass and \( M_v \) (Henry & McCarthy 1993). For the lowest mass stars \( (M_v > 10.25) \) their masses were derived from the available photometry, using theoretical relationships obtained from numerical simulations (Baraffe et al. 1998). The model for stars of solar metallicity and age 1 Gyr was used. The three methods used to obtain masses, demonstrated a high degree of agreement at the crossover points.

For the brighter stars, binarity was indicated in the data base. For the fainter stars, such as those from the survey of Hambly et al. Pinfield (1997) finds that approximately 47 per cent of low-mass stars are binary in Praesepe. Using the available photometry a line was fitted through the sequence on the \( I_c \) versus \( R_c \) plot, and was shifted in a perpendicular direction until 47 per cent of the stars were above the line; these stars were then tagged in the data base as being binary, and the masses were calculated as if each system comprised an equal mass binary. PJH justify this approach.

2.2 The spatial distribution of stars

A contour plot (Fig. 1) was generated to examine the shape of the cluster, and to aid determination of the cluster centre. This was achieved by counting the number of stars in boxes of 1-pc\(^2\) area, and linking points of the same density. This plot indicates the presence of a subcluster some 3 pc away from the centre of the cluster. The cluster centre was taken to be the centre of the highest contour level. For the purpose of the King modelling, the subcluster area was excluded from the analysis.

2.3 The density distribution

King (1962) derived an empirical surface density function that fits the observed surface densities of stars in most globular clusters in which core collapse has not occurred.

\[
\frac{d}{dr} \int f(x) dx = \frac{1}{\sqrt{1 + (r/r_c)^2}} \left( 1 - \frac{1}{\sqrt{1 + (r/r_c)^2}} \right)^2
\]

\[
\frac{d}{dr} \int f(x) dx = \frac{1}{\sqrt{1 + (r/r_c)^2}} \left( 1 - \frac{1}{\sqrt{1 + (r/r_c)^2}} \right)^2
\]

where \( f_s \) is the surface density, \( k \) a normalization constant, \( r \) the radius and \( r_c \) and \( r_t \) the core and tidal radii, respectively. This can be integrated between the centre of the cluster, \( r = 0 \), and \( r = r_t \) to give the total number of cluster stars, \( n \).

\[
n = \frac{\pi}{2} k \left( x + \frac{3}{5} \sqrt{1 + x t} - \frac{3}{5} \right)
\]

where

\[
x = \frac{1}{r_c} \frac{r_t}{r_c}
\]

Equation (3) can be deprojected to give the spatial density of stars \( \varphi(r) \)

\[
\varphi(r) = \frac{1}{\pi} \int \left( \frac{d}{dx} f(x) \right) dx = \frac{k}{\pi r_c (1 + (r/r_c)^2)^{1/2}} \left( 1 - \frac{1}{2} \cos^{-1} \frac{r}{r_t} \right)
\]

where

\[
z = \sqrt{1 + \frac{(r/r_c)^2}{1 + (r/r_c)^2}}
\]
Table 1. Praesepe catalogue sources.

<table>
<thead>
<tr>
<th>Catalogue sources for members</th>
<th>Observation methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klein-Wassink 1927</td>
<td>Photometry and proper motions</td>
</tr>
<tr>
<td>Johnson 1952</td>
<td>Photometry</td>
</tr>
<tr>
<td>Upgren, Weis &amp; DeLuca 1979</td>
<td>Photometry</td>
</tr>
<tr>
<td>Weis 1981</td>
<td>Photometry</td>
</tr>
<tr>
<td>Stauffer 1982</td>
<td>Photometry</td>
</tr>
<tr>
<td>Jones &amp; Cudworth 1983</td>
<td>Photometry and proper motions</td>
</tr>
<tr>
<td>Corbally &amp; Garrison 1986</td>
<td>Positions</td>
</tr>
<tr>
<td>Mermilliod et al. 1990</td>
<td>Photometry and proper motions</td>
</tr>
<tr>
<td>Jones &amp; Stauffer 1991</td>
<td>Photometry and proper motions</td>
</tr>
<tr>
<td>Williams et al. 1994</td>
<td>Photometry</td>
</tr>
<tr>
<td>Hambly et al. 1995</td>
<td>Photometry and proper motions</td>
</tr>
<tr>
<td>Binary information</td>
<td></td>
</tr>
<tr>
<td>Treanor 1960</td>
<td>Spectroscopy</td>
</tr>
<tr>
<td>McGee et al. 1967</td>
<td>Spectroscopy</td>
</tr>
<tr>
<td>Dickens, Kraft &amp; Krzeminski 1968</td>
<td>Photometry and spectroscopy</td>
</tr>
<tr>
<td>Whelan, Worden &amp; Mochnacki 1973</td>
<td>Spectroscopy</td>
</tr>
<tr>
<td>Mermilliod &amp; Mayor 1989</td>
<td>Spectroscopy</td>
</tr>
<tr>
<td>Mermilliod et al. 1990</td>
<td>Spectroscopy</td>
</tr>
<tr>
<td>Bolte 1991</td>
<td>Photometry</td>
</tr>
<tr>
<td>Soderblom et al. 1993</td>
<td>Photometry and spectroscopy</td>
</tr>
<tr>
<td>Mermilliod, Duquennoy &amp; Mayor 1994</td>
<td>Spectroscopy</td>
</tr>
</tbody>
</table>

Figure 1. A surface density contour plot showing the substructure. Each line represents an increment of 10 stars/pc². Numbers are indicated on the lines of density 10, 40 and 70 stars/pc².

The value of \( r_1 \) depends on the mass of Praesepe, the mass of the part of the galaxy that is contained inside the orbit of Praesepe around the galaxy centre, and the radius of Praesepe's orbit from the centre of the galaxy. A first approximation of \( r_1 \) was made for use in the King modelling, by evaluating

\[
  r_1 = 1.46 M_c^{1/3}
\]

(Pinfield et al. 1998), where \( r_1 \) is in parsecs and \( M_c \) is the total mass of Praesepe members in solar masses obtained from the catalogue of selected members.

2.4 The observed Praesepe distribution

Stars were counted in rings 1-pc wide, out from the centre of the cluster; stars in the subcluster area were excluded from this part of the analysis. The surface densities were calculated taking account of the excluded subcluster area and areas of incomplete data in the low mass star surveys (Hambly et al. 1995; Jones & Cudworth 1983).

A Fortran routine call dx_srchmin (Willingdale, private communication) was used to minimize the \( \chi^2 \) statistic and obtain the best-fitting values of \( r_c \) and \( k \) for each mass bin, given an initial value for \( r_c \).

The new values for \( r_c \) and \( k \) enabled the number of stars in each bin to be calculated using equation (3). This, together with the average mass of stars in each bin allowed calculation of the total mass of the cluster, and a new value for \( r_c \) was calculated using equation (8). This was then used as the new value of \( r_c \) for input into the modelling program, and the process was repeated until the value of \( r_c \) inserted into the program was consistent with the modelled total mass of the cluster. Finally, the best-fitting values for \( r_c \) and \( k \) were adjusted within the 1σ limits to ensure that the total number of stars given by the model was consistent with the observed cumulative total. In this way the value obtained for \( r_c \) was 12.1 pc, and the total mass of the cluster (excluding the subcluster) was 626 M☉.

The surface density plots are shown in Fig. 2; the errors used for the surface densities are \( \pm (100/\sqrt{N}) \) per cent. The solid lines indicate the best-fitting surface density profile. Also included are the integrated versions of the King equation (equation 3), with the cumulative total number of stars plotted. The surface densities show good agreement with the best-fitting values for the two highest mass bins, and fair agreement for the two lowest mass bins where the lower star densities result in a greater range of values for \( r_c \) and \( k \) within the 1σ limits.

The results of the \( \chi^2 \) fitting process are summarized in Table 2.

3 THE DYNAMICS OF PRAESEPE

3.1 Calculated velocity dispersions

Using the deprojected King equation (equation 6) the density profiles were calculated, and this in turn was integrated to give the mass as function of radius. The results of this are shown in Fig. 3. Bin 2 (1.2–0.6 M☉) contributes most to the mass of Praesepe, with Bins 1 (3.0–1.2 M☉) and Bin 2 contributing most to the central density of Praesepe.

It can be shown (King 1966; Da Costa & Freeman 1976, PJH) that

\[
  \frac{1}{3} m v^2 = m \langle \sigma^2 \rangle = \left( \frac{4 \pi G}{9} \right) m \rho r_c^2
\]

(9)

where \( \sigma^2 \) is the mean square velocity of stars in a given mass bin, \( \langle \sigma^2 \rangle \) is the mean square velocity in any one coordinate, and \( \langle \sigma^2 \rangle \) is the velocity dispersion.

Using the values obtained for the central density and the core radii for each bin, a calculation of the velocity dispersion for each bin was made, and these are plotted in Fig. 4.

If equipartition of energy had occurred in Praesepe, as might be expected for a cluster of this age, we should expect that \( m \sigma^2 \) is constant and therefore \( r_c \propto m^{-1/2} \). However, as Fig. 4 shows, a parabolic fit, \( r_c \propto (m^{-1/2})^2 \) is a much better representation of our data for the three highest mass bins. \( r_c \propto m^{-1} \) implies that cluster...
Figure 2. On the left side are plots of the observed surface densities for each mass bin, overlaid with a solid line representing the model values for the best-fitting parameters; on the right are the cumulative total star counts, overlaid with the radially integrated version of the King equation for the best-fitting values. The best-fitting values for $r_c$ are indicated by a dotted line.
stars all have the same momentum rather than energy. A surprising result, which could be explained by supposing the cluster has recently been subjected to an impulsive force, such as some kind of collision. Whichever way Fig. 4 is viewed, it is clear that the lower mass stars have too much energy. This is in complete contrast to the results of PJH on the Pleiades, where the lowest mass stars have too little energy and are thus thought not to be fully relaxed.

3.2 Virial analysis

In the context of a star cluster that is in equilibrium and not exchanging energy with external sources, the virial theorem indicates that the cluster binding energy should be related to the kinetic energy of the stars by the following relation

$$\Omega = 2T$$  \hspace{1cm} (10)

where \(\Omega\) is the total binding energy of the cluster stars, and \(T\) is the total kinetic energy of the stars.

The total binding energy of the cluster, \(\Omega\), can be obtained from a numerical integration of

$$\Omega = \int_{r_i}^{r_f} \left( \frac{GM(r)}{r} \right) \left\{ \frac{4\pi r^2 \rho(r)}{m} \right\} \, dr$$  \hspace{1cm} (11)

where \(M(r)\) is the cumulative mass profile and \(\rho(r)\) is the density, both shown in Fig. 3.

The kinetic energy of the cluster stars was calculated by using the values already obtained for the central velocity dispersions of the stars in each mass bin, and assuming that the cluster stars lose energy as they move out, away from the cluster centre, against its gravitational potential. This quantity was calculated for the stars in rings out from the cluster centre, and multiplied by the number of stars in each ring

$$T = \int_{r_i}^{r_f} \left( \frac{3}{2} m(\sigma^2) \right) \left\{ \frac{4\pi r^2 \rho(r)}{m} \right\} \, dr$$  \hspace{1cm} (12)

Table 2. The results of the King modelling for Praesepe.

<table>
<thead>
<tr>
<th>Bin</th>
<th>Mass range</th>
<th>Average mass (pc)</th>
<th>(R_c) limits (68 per cent conf)</th>
<th>(r_i) limits (68 per cent conf)</th>
<th>(N)</th>
<th>(M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5–1.2</td>
<td>1.60</td>
<td>1.10 (0.78–1.10)</td>
<td>12.0 (8.4–13.6)</td>
<td>95</td>
<td>151</td>
</tr>
<tr>
<td>2</td>
<td>1.2–0.6</td>
<td>0.84</td>
<td>1.75 (1.56–1.97)</td>
<td>22.0 (18.1–23.8)</td>
<td>305</td>
<td>256</td>
</tr>
<tr>
<td>3</td>
<td>0.6–0.25</td>
<td>0.42</td>
<td>4.28 (3.74–4.67)</td>
<td>14.2 (12.5–14.9)</td>
<td>349</td>
<td>147</td>
</tr>
<tr>
<td>4</td>
<td>0.25–0.1</td>
<td>0.17</td>
<td>6.50 (5.80–7.35)</td>
<td>19.3 (17.0–20.2)</td>
<td>424</td>
<td>72</td>
</tr>
</tbody>
</table>

\(r_i = 12.1\) pc; \(M_c = 626\) M\(_\odot\)

Figure 3. The deprojected density profiles and mass profiles for the four mass bins are indicated by different line types. Also shown are the total density and total mass of Praesepe as indicated by the solid line.

where \(M(r)\) is the cumulative mass profile and \(\rho(r)\) is the density, both shown in Fig. 3.

The kinetic energy of the cluster stars was calculated by using the values already obtained for the central velocity dispersions of the stars in each mass bin, and assuming that the cluster stars lose energy as they move out, away from the centre of the cluster, against its gravitational potential. This quantity was calculated for the stars in rings out from the cluster centre, and multiplied by the number of stars in each ring

The first term, \((3/2)m(\sigma^2)\), is the value for the kinetic energy of a star in the centre of the cluster, obtained from the central velocity dispersion calculated from equation (9); the \(m\psi(r)\) term is the gravitational potential that the cluster stars have to move against as they move away from the cluster centre, and the bracketed term is the total number of stars in a ring of radius \(r\) and thickness \(dr\). The results of this calculation for Praesepe are shown in Table 3. It is clear that the total cluster kinetic energy is about six times higher than expected; it is the stars in the two lower mass bins that appear to have too much energy.
4 X-RAY DATA

X-Ray surveys (Randich & Schmitt 1995; Barrado y Navascués et al. 1998) have found an anomalous X-ray luminosity function for Praesepe, which sits significantly below the age-equivalent Hyades X-ray luminosity function.

If the X-ray detected sources in Praesepe from the ROSAT survey are overlaid on a density plot for the cluster (generated in the same way as the density plot) then it can be seen that the brightest X-ray stars are found almost exclusively in the main cluster (see Fig. 5).

This may indicate that there could be an age difference between the main cluster and the subcluster.

5 CONCLUSIONS

This work has extended the study of Praesepe to lower mass stars than before, and much of the work has provided some surprising results.

First, the contour and density plots show the existence of a subcluster of mass approximately 30 M_☉, 3 pc away from the centre of the cluster. As numerical simulations suggest that such structures disperse over the order of a crossing time (around 10 Myr), then the arrival of the subcluster must be fairly recent.

Secondly, the core radii for various stellar mass bins fit \( r_c \propto m^{-1/2} \), and the low mass cluster stars therefore appear to have excess energy. We suggest that this may be the result of a recent collision with the subcluster.

Thirdly, the virial analysis implies that there is far too much kinetic energy in the cluster; so much so, that it must be in the process of flying apart. This might also be a direct result of a collision.

Finally, the anomalous X-ray results suggest that there may be an age difference between the main cluster and the subcluster.

Taking all these conclusions together it is tempting to suggest that the present cluster is the result of a recent merging of two clusters. The energy of the collision will cause Praesepe to disintegrate rapidly in the future.

ACKNOWLEDGMENTS

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