The directional analysis of star clusters

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ABSTRACT

We introduce the Fry Plot and demonstrate its use in quantifying the directionality in star clusters. Taurus and IC2391 are both found to demonstrate a bias in the Probability Density Function (PDF) for neighbours in the same direction for both small and large separations. The Chamaeleon I cluster and Orion B North star-forming region, by contrast, show a symmetrical PDF at small scales, but a directional bias at large scale. Rho Ophiucus, NGC 1333, IC348 and Serpens Main show broadly symmetrical distribution of neighbours. The Pipe Nebula shows strong directional bias at all scales due to the existence of a dominating linear feature. This technique will be useful for quantifying features in observed and simulated objects, and for comparisons with other directional information, such as polarization, velocity and magnetic field maps.

Key words: methods: data analysis – open clusters and associations: general.

1 INTRODUCTION

Since most stars are formed in clusters, it is useful to have quantitative and objective statistical measures of their structure, with a view to comparing clusters formed in different environments, and tracking changes in structure as clusters evolve. This is particularly important for young, embedded clusters, where the structure may yield important clues to the formation process but is changing rapidly. It is also important for comparing observed clusters with numerical simulations.

A widely used technique in this field is the log/log plot of the Mean Surface Density of Companions (MSDC), as pioneered by Larson (1995) and subsequently used by several others (e.g. Bate, Clarke & McCaughrean 1997; Simon 1997; Brandner & Köhler 1998; Nakajima et al. 1998; Gladwin et al. 1999; Klessen & Kroupa 2001). Cartwright & Whitworth (2004) introduced a dimensionless measure, $Q$, capable of both quantifying and distinguishing between radial and multiscale (fractal type) clustering. This method has been applied successfully to the analysis of both real observations (Cartwright & Whitworth 2004; Cartwright, Whitworth & Nutter 2006; Kumar & Schmeja 2007; Caballero 2008) and numerical results (Schmeja & Klessen 2005). The protocol for using $Q$ has recently been extended to permit application to more elongated structures (Cartwright & Whitworth 2008).

Both $Q$ and MSDC methods discard all directional information, simply manipulating the scalar distances between stars, and therefore revealing nothing about the symmetry or directionality of a cluster. However, external influences such as radiation, collision or shocks have been proposed as triggers for star formation (e.g. Elmegreen & Lada 1977; Whitworth & Zinnecker 2004; Whitworth 2007; Kisionas et al. 2008) and such directional phenomena might be expected to be imprinted upon the structure of the molecular clouds, and hence upon the distribution of the resulting prestellar cores and young stars. A large-scale magnetic field might also leave its imprint on the pattern of star formation in a molecular cloud. Techniques permitting objective measurement of the directionality of structure would therefore be helpful in testing these hypotheses.

Some effort has recently been made to establish such techniques. Gutermuth’s Azimuthal Assymetry Index (2008a) divides a cluster into slices like a pie, and compares the contents of the slices with a Gaussian model. The variation of the contents of the segments from the model, and from each other, provides a measure of asymmetry, but cannot distinguish whether the variation is at large or small scales. Cartwright & Whitworth (2008) used a very simple measure of Aspect Ratio, which measures the variation from circularity of the outer envelope of a cluster, which only registers the assymmetry at large scales.

Here, we introduce a technique originating in Geophysics, the Fry Plot, which permits an analysis of favoured directions of companions, at all scales, within a cluster of points. In Section 2, we describe the origin of the real and artificial data sets used. In Section 3, we outline the methodology and produce Fry Plots of artificial star clusters. In Section 4, we present Fry Plots of eight real star clusters. Our results are discussed in Section 5, and the main conclusions are summarized in Section 6.

2 DATA SOURCES

2.1 Artificial clusters

A detailed description of the methods used for creating artificial star clusters with known characteristics is given in Cartwright
2.2 Observed star clusters

Data from real clusters in Taurus, Serpens, Chamaeleon I, IC2391, IC348, Rho Ophiuchus and NGC 1333 were used, as well as a survey of prestellar objects in the Pipe Nebula. All clusters were first normalized by centering them on the centre of mass of the whole cluster, and then setting the unit distance as the distance to the farthest point. The normalized raw data are shown in Figs 1 and 2, together with the value of Q and the Aspect Ratio for each cluster. The line indicates the direction of long axis which yields the smallest value of Aspect Ratio for each cluster. The Clusters are shown in order of increasing Q. The clusters in Fig. 2 all have $Q \leq 0.8$, indicative of fractal type, multiscale subclustering, decreasing in severity from top (Taurus, fractal dimension $D \approx 1.6$) to bottom (IC2391, $D \approx 2.25$). The clusters in Fig. 1 all have $Q \geq 0.8$ indicating smoothly varying, radial-type clustering, increasing from top ($\rho$ Ophiuchus, density proportional to $r^{-\alpha}$, $\alpha \approx 1.2$) to bottom (Serpens, $\alpha \approx 2.1$). Table 1 lists the sources of the data.

2.3 Submillimetre maps of the Orion B North star-forming region

850 μm maps of the Orion B North star-forming region were obtained using the Submillimetre Common User Bolometer Array (SCUBA) at the James Clerk Maxwell Telescope (JCMT). For details of the data acquisition and reduction, see Nutter & Ward-Thompson (2007). The mapped area contains the two optical nebulae NGC 2068 and NGC 2071. This region is known to be a site of ongoing star formation (Johnstone et al. 2001; Motte et al. 2001). The cloud is just over 5 pc across. The whole image is $637 \times 919$ pixel.

Table 1. Sources of positions for cluster members.

<table>
<thead>
<tr>
<th>Name</th>
<th>Members</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Nebula</td>
<td>159</td>
<td>Alvez et al. (2007)</td>
</tr>
<tr>
<td>IC2391</td>
<td>166</td>
<td>Barrado y Navascues et al. (2001)</td>
</tr>
<tr>
<td>$\rho$ Ophiuchus</td>
<td>199</td>
<td>Bontemps et al. (2001)</td>
</tr>
<tr>
<td>ngc1333</td>
<td>137</td>
<td>Gutermuth et al. (2008b)</td>
</tr>
<tr>
<td>IC348</td>
<td>288</td>
<td>Luhman et al. (2003)</td>
</tr>
<tr>
<td>Serpens Main</td>
<td>137</td>
<td>Winston et al. (2007)</td>
</tr>
</tbody>
</table>

3 RESULTS

3.2 Fry Plots of grey-scale data

Fry Plots may also be produced using grey-scale data. The original map is first examined, identifying each pixel $i$ with contents greater than some threshold value, and then repeatedly repositioning the map with position $p_i$ in turn as the origin. The grey-scale values $p_{ij}$ from each neighbouring pixel at position $p_i$ are accumulated into the Fry plot pixel at position $p_i - p_j$. Note that this can be a much more time consuming process than the construction of a Fry Plot from point data, and that great care must be taken when accumulating large numbers of small values.

4 RESULTS

Figs 1 and 2 show the contoured Fry Plots for all eight real data sets. Fig. 2 shows star clusters which have been classified as fractal type, based on their $Q \leq 0.8$. The Fry Plot for Taurus shows that there are two peaks in the distribution of neighbours. There is a very close peak at small scales, $s < 0.1$, and this should probably be attributed to pairs of stars in the same subcluster. There is also an excess of separations on large scales, $s \sim 0.5$, which can be attributed to
Figure 1. Raw data and contoured Fry Plots for all four real, radially subclustered star clusters. Left-hand side, the clusters have been centred on the mean position of all stars and scaled so that the distance from the centre to the most distant star is unity. The line indicates the direction of projection which resulted in the maximum value of Aspect Ratio, $A$, and that value is shown for each cluster. The value of $Q$ increases from top to bottom, indicating decreasing radial clustering, $\alpha \simeq 1.2, 1.8, 2.0$ and 2.1. Right-hand side, the contoured Fry plots for the four clusters. $n_{\text{max}}$ is the number of neighbouring stars found in the most densely populated bin of the Fry Plot, normalized by dividing by $N^2_{\text{stars}}$. For a random distribution of stars, the empirical value of $n_{\text{max}} \simeq 0.0029$. 

Figure 2. Raw data and contoured Fry Plots for all four real, fractally subclustered star clusters. Left-hand side, the clusters have been centred on the mean position of all stars and scaled so that the distance from the centre to the most distant star is unity. The line indicates the direction of projection which resulted in the maximum value of Aspect Ratio, $A$, and that value is shown for each cluster. The value of $Q$ increases from top to bottom, indicating increasing fractal dimension $D \approx 1.6, 1.75, 2.4, 2.25$. Right-hand side, the contoured Fry plots for the four clusters. nmax is the number of neighbouring stars found in the most densely populated bin of the Fry Plot, normalized by dividing by $N^2/2$. For a random distribution of stars, the empirical value of nmax $\approx 0.0029$.

Chamaeleon reveals no significant directionality of neighbours at any scale, whereas IC 2391 reveals a well-defined excess of EW separations on intermediate scales $0.2 \lesssim s \lesssim 0.4$.

Fig. 1 shows clusters which have $Q \gtrsim 0.8$ and are therefore radially subclustered. The contoured Fry Plots for Rho Ophiucus, ngc 1333 and IC348 are all noticeably smooth and regularly spaced, when compared with the plots for artificial clusters of similar size with radial density gradients. Although there is only slight directionality shown in the contours, the directionality persists at all scales.

The Fry Plot for Serpens shows no directionality at large scales, but a preferred north–south direction for neighbours at small scales, characterising the distribution of stars in the central, high-density region.

Fig. 4 shows the effect of including all neighbours in the Fry Plots, rather than including only neighbours for $s \leq 0.5$. Taurus and the Pipe Nebula now show parallel offsets of the main central alignments, due to the existence of clusters of points away from the main alignments. The Chamaeleon Fry Plot now shows a second maximum for neighbours at a distance of $s \approx 1.0$, slightly west of north, which points to the existence of two main subclusters within the cluster. The IC2391 plot shows that the marked excess of neighbours in the east–west orientation extends further than half the cluster radius to $s \approx 1.0$.

4.1 Fry Plots of grey-scale data

Fig. 5 shows the raw data from the Orion B North star-forming region, and the Fry Plot obtained from the data. Data were only included for $s \leq 0.5$. Twenty contour levels were set, evenly spaced from zero to maximum density, but for clarity, only the bottom 10 contours were plotted. The top 10 contours simply formed nested, symmetrical circles inside the maxima. The maximum in the Fry Plot is centred on the origin and symmetrical, and this characterizes the distribution of neighbouring material within the subfeatures of the region. The symmetry is surprising given the apparent asymmetry of the subfeatures, and is not apparent to the naked eye. The large secondary maximum at $s \approx 0.5$, slightly west of north, reflects the strong directional bias in the separation between features in this direction. The contours reveal more detail of the distribution of neighbouring material at less than 50 per cent of the maximum density, and there is a tendency for this material to be aligned more east to west.

5 DISCUSSION

The Fry Plot is able to quantify and contrast asymmetry in the Probability Density Function (PDF) for neighbouring stars within star clusters. Unlike other methods, variations between small-scale and large-scale effects can be captured. For example, the Orion Nebula shows no asymmetry in the likelihood of neighbouring dense regions at small scales, but a strong directional maximum at larger scales, of the order of the size of half the overall cloud. Taurus, by contrast, shows a high likelihood of neighbouring stars in the NW/SE direction, both at small intrasubcluster and large intersubcluster scales. The radially subclustered objects, Rho Ophiucus, NGC 1333 and IC348 are found to have symmetrical PDFs, but the most severely radially clustered object, Serpens Main, is found to have a directional bias at small distances. The existence of asymmetry in the PDF is not, however, found simply to be an indicator of the severity of clustering, as cluster IC2391 is found to demonstrate asymmetry at all scales, but is one of the least severely clustered of the eight clusters analysed.
The directional analysis of star clusters

Figure 3. Fry plots for artificial star clusters. (a) Fry plot for points randomly distributed over a three-dimensional sphere and then projected into two dimensions; (b) surface density contours for (a), contours at 10 per cent intervals of maximum surface density; (c) Fry Plot for artificial star cluster with radial density gradient $\sigma \propto r^{-2}$; (d) 10 per cent contour plot of (c); (e) Fry Plot of artificial star cluster with fractal dimension 2.5; (f) contour plot of (e). All clusters created with 180 members.

It should be noted that if a Fry Plot is azimuthally averaged to produce a radial surface density profile, the resulting plot is the MSDC, a descriptor more familiar to Astronomers.

6 CONCLUSION

The Fry Plot presents a convenient technique for quantifying and displaying any directional bias in the PDF for neighbouring material in a star cluster. It can be used to analyse the distribution of groups of points, be they stars of prestellar cores, or the distribution of matter represented in pixelated or grey-scale maps, usefully allowing comparisons between these two types of objects. Correlation will also be possible between Fry Plot directional data and, for example, polarization and magnetic field maps.

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REFERENCES

Figure 4. Contoured Fry plots showing the full extent of neighbours for all stars. (a) Taurus; (b) Pipe Nebula; (c) Chamaeleon; (d) IC2391. Taurus and the Pipe Nebula do not show any more interesting features. The Chamaeleon Fry Plot now shows a second maximum for neighbours at a distance of 1.2 cluster radii slightly west of north and reflects the existence of two main subclusters within the cluster. The IC2391 plot shows that the marked excess of neighbours in the east–west orientation extends further than half the cluster radius.

Figure 5. Orion B North. Left-hand side, the raw data, and right-hand side, the contoured Fry Plot. Contours 1–10 of 20 are plotted.
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