Why do starless cores appear more flattened than protostellar cores?

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ABSTRACT

We evaluate the intrinsic three dimensional shapes of molecular cores, by analysing their projected shapes. We use the recent catalogue of molecular line observations of Jijina et al. and model the data by the method originally devised for elliptical galaxies. Our analysis broadly supports the conclusion of Jones et al. that molecular cores are better represented by triaxial intrinsic shapes (ellipsoids) than biaxial intrinsic shapes (spheroids). However, we find that the best fit to all of the data is obtained with more extreme axial ratios (1 : 0.8 : 0.4) than those derived by Jones et al.

More surprisingly, we find that starless cores have more extreme axial ratios than protostellar cores – starless cores appear more ‘flattened’. This is the opposite of what would be expected from modeling the freefall collapse of triaxial ellipsoids. The collapse of starless cores would be expected to proceed most swiftly along the shortest axis – as has been predicted by every modeller since Zel’dovich – which should produce more flattened cores around protostars, the opposite of what is seen.

Key words: stars: formation

1 INTRODUCTION

Stars form in dense interstellar regions known as molecular clouds, and particularly in the densest cores of molecular clouds. A great deal of observational work on molecular cloud cores has been carried out and a large number of sites of star formation have been observed in various molecular transitions (e.g. Myers, Linke & Benson 1983; Myers & Benson 1983; Benson & Myers 1989). The chief transitions used tend to be various isotopes of CO (a tracer
of column density) and NH$_3$ (a tracer of volume density). A recent paper (Jijina, Myers & Adams 1999) cataloged all of the known molecular observations of a large sample of nearby star-forming regions, listing many of their physical properties such as density, temperature, size and shape. Such a catalogue provides a wealth of detailed information about the star formation process. In this letter we concentrate on what we can learn from this catalogue about the shapes of star-forming cores.

When observing molecular cloud cores, all we see are their projected shapes on the sky, whilst for detailed comparison with theory we would like information on their three dimensional shapes. Jijina et al. (1999) used their molecular-line maps of molecular cores and estimated the projected axial ratios ($q$) by fitting elliptical envelopes to the data. Here we analyze the resulting distribution of projected axial ratios, on the assumption that molecular cores are ellipsoidal, with a well-defined distribution of intrinsic axial ratios ($1 : \zeta : \eta$), and that the cores in the Jijina et al. sample are randomly oriented. Our aim is to constrain the distribution of intrinsic three-dimensional axial ratios.

## 2 DEPROJECTING ELLIPTICITY

A triaxial object, when viewed from any angle, appears in projection as an ellipse. Binney (1985) calculated the projected axial ratio $q$ ($= b/a \lesssim 1$) for an ellipsoid having axial ratios $1 : \zeta : \eta$ (where $\eta \leq \zeta \leq 1$) and viewed from an angle $(\theta, \phi)$ as

$$q = \frac{A + C - \sqrt{(A - C)^2 + B^2}}{A + C + \sqrt{(A - C)^2 + B^2}},$$

where $A$, $B$ and $C$ are functions of the intrinsic axial ratios and the viewing angles given by

$$A = \frac{\cos^2(\theta)}{\eta^2} \left[ \sin^2(\phi) + \frac{\cos^2(\phi)}{\zeta^2} \right] + \frac{\sin^2(\theta)}{\zeta^2},$$

$$B = \cos(\theta)\sin(2\phi) \left[ 1 - \frac{1}{\zeta^2} \right] \frac{1}{\eta^2},$$

and

$$C = \left[ \frac{\sin^2(\phi)}{\zeta^2} + \cos^2(\phi) \right] \frac{1}{\eta^2}.$$

The simplest statistical approach to take in determining whether a given distribution of projected axial ratios ($q$) is drawn from a single distribution of intrinsic axial ratios ($\zeta, \eta$), is to use an assumed distribution of $\zeta$- and $\eta$-values to generate a large number (more than $10^5$) of projected $q$-values in a Monte Carlo simulation. These Monte Carlo $q$-values can be
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converted into a distribution function, and this ‘artificial’ distribution function can then be compared with the ‘real’ (i.e. observed) distribution function from the Jijina et al. data set. The KS-test and $\chi^2$ test can be used to evaluate the likelihood of the assumed fit.

Following Jones, Basu & Dubinski (2001), we assume that the axial ratios $\zeta$ and $\eta$ have Gaussian distributions characterized by means ($\bar{\zeta}, \bar{\eta}$) and standard deviations ($\sigma_\zeta, \sigma_\eta$), with the additional constraint that $\zeta$ and $\eta$ must fall in the interval from 0 to 1.

3 RESULTS

We find that the best fit to the observed $q$-values of the entire Jijina et al. (1999) sample is obtained with $\bar{\zeta} \simeq 0.8, \sigma_\zeta \simeq 0.1$, $\bar{\eta} \simeq 0.4$ and $\sigma_\eta \simeq 0.2$. It has $\chi^2$ probability of 0.74. In contrast, Jones et al. (2001) find $\bar{\zeta} \simeq 0.9, \bar{\eta} \simeq 0.5$ and $\sigma_\zeta \simeq \sigma_\eta \simeq 0.1$. This difference is significant at the high ellipticity end of the distribution (but not in the heart of the distribution as both are good fits to the data). To test this $10^5$ ellipticities were drawn from both our best fit and that of Jones et al. and the KS test rejects the two distributions as being the same at very high probability ($> 95$ per cent). The rejection is at even higher significance for less than $10^5$ samples.

The reason why our analysis rejects the Jones et al. (2001) best fit is that the smallest observed axial ratio $q = 0.175$ requires the combination of an extremely small short axis ($\sim 3\sigma_\eta$ below $\bar{\eta}$) and a viewing direction within a few degrees of the mid-axis. This is extremely unlikely. Moreover it should be noted that the $q = 0.175$ core is not a lone outlier; there are four cores with $q < 0.25$.

Jijina et al. (1999) find significant differences in many of the cores’ properties between starless cores (ones with no associated IRAS source) and protostellar cores (ones with at least one associated IRAS source). They also find significant differences between cores which are associated with star clusters and those which are not. We therefore repeated our analysis for these subsamples. Association with a star cluster does not appear to affect the distribution of intrinsic axial ratios.

However, there does appear to be a statistically significant difference between starless cores and protostellar cores. There are 79 starless cores and 179 protostellar cores in the sample, excluding cores defined by Jijina et al. (1999) as being multiples, due to the difficulties of correctly determining the projected axial ratios of such cores.

Figure 1 shows the best fit for starless cores, obtained with $\bar{\zeta} = 0.8, \sigma_\zeta = 0.1, \bar{\eta} = 0.3,$
Figure 1. The best fit to the sample of 79 starless cores with axial ratios 1:0.8:0.3 with 1\(\sigma\) spreads of 0.1 on the mid axis and 0.2 on the short axis. The bars show the \(\sqrt{n}\) errors for each bin.

Figure 2. The best fit to the sample of 179 protostellar cores with axial ratios 1:0.8:0.5 with 1\(\sigma\) spreads of 0.1 on the mid axis and 0.2 on the short axis. Again the bars show the \(\sqrt{n}\) errors for each bin.

and \(\sigma_\eta = 0.2\). This fit maximises the KS probability at 0.46 (with a \(\chi^2\) probability of 0.85), a reasonable fit to the data.

Figure 2 shows the best fit for the protostellar cores, obtained with \(\bar{\zeta} = 0.8\), \(\sigma_\zeta = 0.1\), \(\bar{\eta} = 0.5\), and \(\sigma_\eta = 0.2\). This fit has a KS probability of only 0.01 (but a \(\chi^2\) probability of 0.83). Whilst this is the best fit it appears that a distribution formed so simply is not good at representing the observed distribution. The results are summarised in table 1.
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Figure 3. The cumulative distribution functions of starless cores (open circles) and protostellar cores (filled triangles) and an ‘average’ fit of $1:0.8 \pm 0.1:0.4 \pm 0.2$. Note how the starless cores almost all lie above the line and the protostellar cores almost all lie below the line, indicating that starless cores are in general more flattened than protostellar cores.

Figure 3 demonstrates the fact that starless and protostellar cores have significantly different distributions, by comparing their cumulative distribution functions with our average fit obtained using $\bar{\zeta} = 0.8$, $\sigma_\zeta = 0.1$, $\bar{\eta} = 0.4$, and $\sigma_\eta = 0.2$. Evidently neither data set is matched especially well by this average fit. Instead, the average fit lies comfortably between the two cumulative distributions, with the majority of starless cores lying above the average fit, and the majority of protostellar cores lying below it. This difference is significant as the KS test shows that starless and protostellar cores only have a 5 per cent probability of being drawn from the same distribution.

To test whether the apparent difference between starless cores and protostellar cores is due to selection effects, we examined whether $q$ correlates with properties such as the linear size and density of a core. In the Jijina et al. data set, the protostellar cores are generally larger than the starless cores. We believe this to be a selection effect, since a protostellar core is on average hotter and more luminous than a starless core of the same mass, and therefore the outer parts of its envelope are more readily detected. However $q$ is uncorrelated with other properties (in particular linear size) and so we do not believe that selection effects are biasing our results significantly.

If selection effects cannot explain our result, then it is surprising. As explained by Zel’dovich (1970), and verified by many others since, one would expect a dynamically collapsing triaxial ellipsoid to collapse faster along its shortest axis than along the other axes.
Consequently, more evolved cores (those with protostars) might be expected to have more extreme axial ratios than less evolved ones (starless cores), which is the opposite of our result. One possible explanation is that the collapse of cores with significant magnetic fields is not as simple as a pure gravitational collapse and may cause the effect we observe (eg. Habe et al. 1991). Another possibility is that the outer envelopes of protostellar cores are not collapsing and have greater isotropic support than those of starless cores. For instance, they could have higher turbulence, as inferred from the broader line-widths observed by Beichman et al. (1986). We are currently undertaking a programme of simulations of the collapse of triaxial cores, which may shed light on the evolution of the axial ratios.

4 CONCLUSIONS

We have shown that the projected axial ratios of molecular cores (Jijina et al. 1999) can be well fitted with randomly oriented ellipsoids having their intrinsic axial ratios distributed according to $\bar{\zeta} \simeq 0.8$, $\bar{\eta} \simeq 0.4$ and $\sigma_\zeta \simeq \sigma_\eta \simeq 0.1$. This conclusion is different to that of Jones et al. (2001) in that they infer less extreme axial ratios. The reason for this is that they allow distributions which (in effect) predict no low $q$-values even though several are observed.

When we divide the Jijina et al. (1999) data into subsamples and repeat our analysis we find a difference between starless cores and protostellar cores, in the sense that starless cores are flatter. Specifically, starless cores are best fit with $\bar{\eta} \simeq 0.3$, while protostellar cores are best fit with $\bar{\eta} \simeq 0.5$. This result is surprising. A triaxial ellipsoid in free-fall should collapse faster along its shortest axis than along the other axes. Hence older cores (those with protostars) might be expected to have more extreme axial ratios. It appears that the opposite is the case.

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