Chapter 13
Kinematics of Star-Forming Regions

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13.1 Introduction

The previous chapters on star-forming regions have focused on spatial distributions of gas and stars. Here we focus on the internal kinematics, the motions of the young stars within the star-forming regions.

The Taurus-Auriga star-forming region, both the molecular gas and the stars, provides an excellent example of the kinematic scales of star-forming regions. This region has been studied extensively, including millimetre-wavelength maps, stellar proper motions and stellar radial velocities. Table 13.1 provides several measures of the internal kinematics.

The velocity dispersion between nearby dense molecular cores, that is the dispersion amongst the velocity centroids of dense molecular cores within groups, is very small, of order 0.5–1.0 km s^{-1}. The global gas velocity dispersion over the entire region is larger, 1–2 km s^{-1}. Figure 13.1 shows the position-velocity plot for the gas. Ignoring for the moment the separate Perseus cloud east of $3^{h}30^{m}$, one is struck by how narrow the distribution is in velocity, showing the small local velocity dispersion. That it is aligned vertically indicates that the global velocity dispersion also is small. So this is a very quiet dynamical system. This is fairly characteristic for those giant molecular clouds in which there are no OB stars at the moment, which is to say no major global energy input. Indeed the Orion cloud as a whole is a very quiet system, away from the regions where there are embedded OB stars.

Furthermore, the mean velocity difference between the gas and the stars is consistent with zero (though it is difficult to reconcile the absolute velocity scales to better than 0.5 km s^{-1}; see e.g. Cottaar et al. 2014). The stellar velocity dispersions within the clumps of young stars are also small. The global stellar velocity dispersion of the

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Table 13.1 Kinematic scales in Taurus-Auriga

Kinematic diagnostic	km s^{-1}
Local gas velocity dispersion	0.5
Global gas velocity dispersion	1–2
Local stellar velocity dispersion	$<$1–2
Global stellar velocity dispersion	2
$v_{star} - v_{gas}$	0.2 ± 0.4

References: Jones and Herbig (1979), Hartmann et al. (1986) and Ungerechts and Thaddeus (1987)

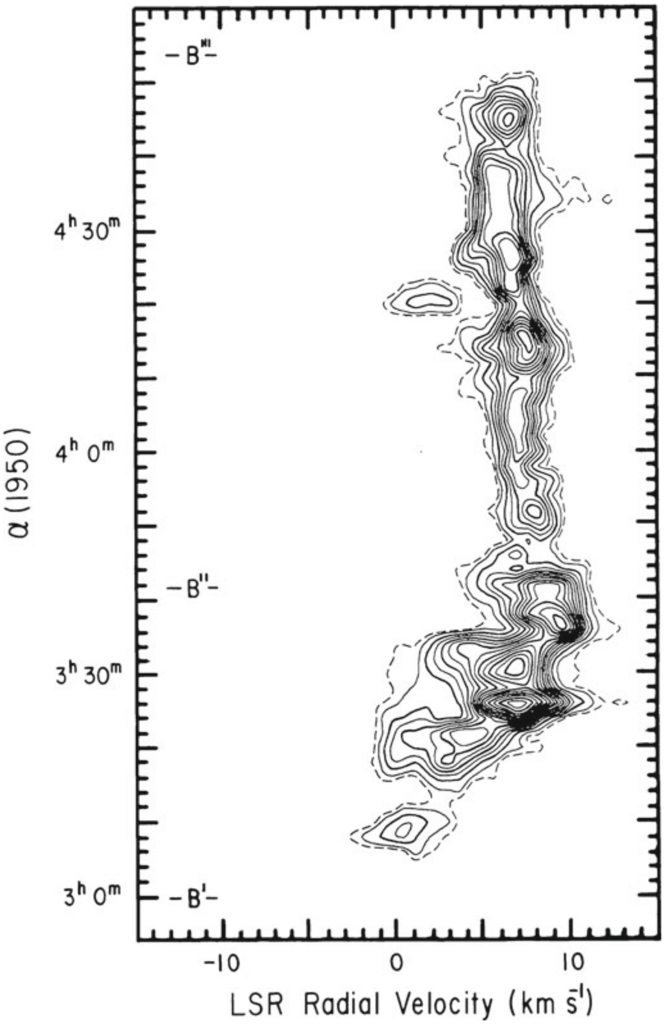

Fig. 13.1 Space-velocity diagram of CO (1-0) line temperature along a cut across the Taurus-Auriga and Perseus molecular cloud complexes. Figure from Ungerechts and Thaddeus (1987)

stars is about 2 km s^{-1}, although this is a somewhat difficult measurement to make. So these are also very quiet stellar systems. This makes the observational study of the internal motions of the young stars in star-forming regions a technical challenge.

13.2 OB Associations After *Hipparcos*

The *Hipparcos* mission was a wonderful bookend to the career of Adriaan Blaauw and in particular to his studies of OB associations, for his classic papers in the early 1960s were the first major studies of the internal kinematics of star-forming regions. At the time the major observational question was the expansion rate of OB associations, building from the earlier theoretical work arguing that they must be unbound. The proper motion studies of Blaauw demonstrating such expansion remain classics in our field.

The contribution of *Hipparcos* to the field was primarily in the domain of kinematic membership of these associations, extending down to B, A and F stars. Nearby associations are distributed over large areas of the sky. At the same time they are no longer associated with gas and dust, and thus confusion with field stars limits secure identification of members of lower mass than the short-lived OB stars. Figure 13.2 shows a proper motion map of the Scorpius-Centaurus association, in this case showing 532 members selected from 4156 *Hipparcos* stars in this region of the sky. The co-movement of the association is very clear.

As Blaauw pointed out 50 years ago, if the sub-associations are unbound and expanding then the sequence of different surface densities evident in Fig. 13.2 represents a sequence of ages. (Here 'age' means the time since the natal gas was removed and the system became unbound.) From this perspective, Lower Centaurus is the oldest part of this system and Upper Scorpius is the youngest. At higher Galactic

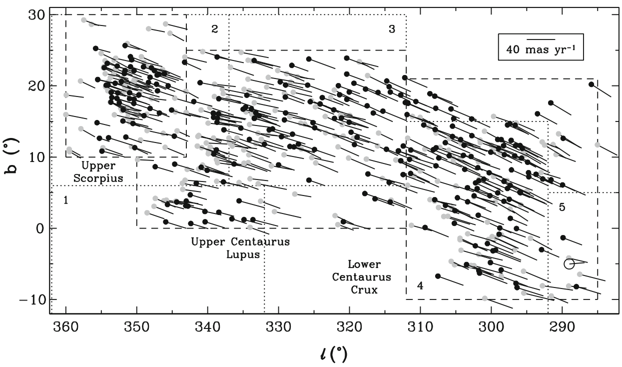

Fig. 13.2 *Hipparcos* positions and proper motions for 532 members of the Scorpius-Centaurus association, with three sub-associations identified. Figure adapted from de Zeeuw et al. (1999)

longitude, just off the figure, is the Ophiuchus molecular cloud in which active low-mass star-formation continues today. Presumably at one time this entire region was a giant molecular cloud, of which the Ophiuchus cloud is the last vestige. Indeed this region is often cited as an example of sequential star formation across a giant molecular cloud, with the star formation in each sub-region ended by a supernovae which then generated star formation in the adjacent region. Another possibility, of course, is that for reasons in the nature of the cloud itself that we do not understand this sequence of formation happened without any particular causal connection. Even so, each region might still be sequentially unbound by supernovae at different eras. We had hoped to obtain internal velocity dispersions, i.e. the differences between the vectors in Fig. 13.2, from *Hipparcos*, but the available precision only placed upper limits of 1–1.5 km s^{-1}. It is in this area that *Gaia* will shine.

13.3 Kinematics in Star-Forming Associations

We begin again with the λ Orionis region as a case study. As a reminder, there are 11 OB stars in a central clustering. Figure 13.3 shows *Hipparcos* proper-motion vectors for the brighter of the OB stars, shown for motions over the past 3 Myr. Given the current physical proximity of these OB stars, clearly they were not unbound 3 Myr ago—indeed, with these proper motions their current radius suggests that they were bound as recently as 1 Myr ago. Given their ages of order 7 Myr, the stars were orbiting in a bound clump of stars and gas for most of their lifetimes. Likely they were actually even more concentrated than presently.

Now with the lower-mass stars in the vicinity of the clump, precise radial velocity measurements with precisions of about 0.7 km s^{-1} have been achieved, especially for those stars that are not actively accreting. The active mass accretion leads to veiled spectra and emission lines which make it more difficult to obtain high precision.[1] Fortunately, whether the OB stars accelerated their disc evolution or because normal evolution has simply depleted the discs around many of these stars, most of the low-mass stars in the λ Ori region are not classical T Tauri stars. We find a radial velocity dispersion of about 2.2 km s^{-1} for the low-mass stars in the vicinity of the OB stars. And indeed, the dispersion of the proper motion measurements for the OB stars is also 2.5 km s^{-1}.

This region is also identified as the open cluster Collinder 69. But is it in fact bound? We can use a very generalised version of the viral theorem

$$\frac{1}{2}\sigma^2 = \frac{GM_{\text{bound}}}{R}, \qquad (13.1)$$

[1] Recent large internal surveys, such as the Sloan Digital Sky Survey III APOGEE IN-SYNC Project, have been able to reach internal consistency of <0.3 km s^{-1} (see e.g. Cottaar et al. 2014). This requires a comprehensive modelling effort, a very large database of observations to control for most systematic issues, and sophisticated data reduction efforts.

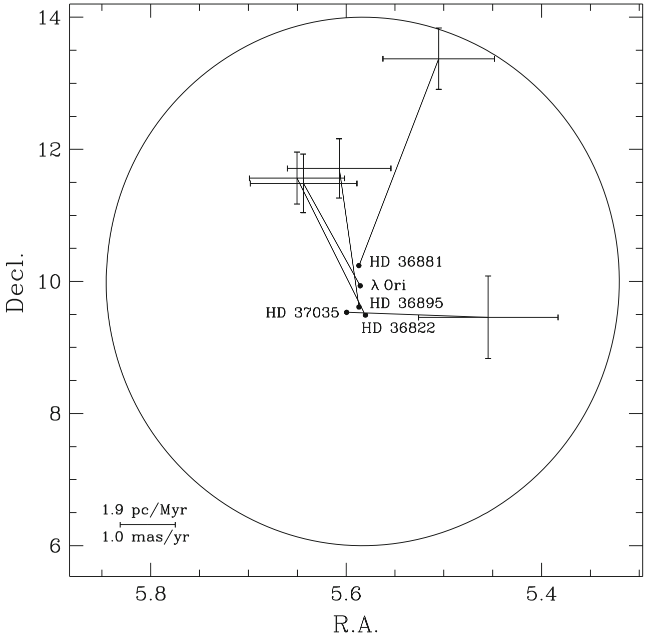

Fig. 13.3 Positions 3 Myr ago of 5 OB stars in the central clump of the λ Ori association, based on *Hipparcos* proper motion data. The error bars are derived from proper motion errors. The circle schematically indicates the position of the ionisation front at the present epoch. Figure from Dolan and Mathieu (1999)

in addition to values for the velocity dispersion and radius of the region ($\sigma \simeq 2.2\,\mathrm{km\,s^{-1}}$ from above and $R \simeq 2\,\mathrm{pc}$) to estimate that a mass of $\sim 1000\,\mathrm{M_{\odot}}$ is required to bind the system. There are about 10 OB stars, representing about $100\,\mathrm{M_{\odot}}$ or so. There are about 70 solar-type stars and about 200 lower-mass stars that have been found (see e.g. Bayo et al. 2011). The required mass definitely is not present in the stars.[2] Clearly, that a substantial mass of gas, more than the stellar mass, was needed to hold this system together for several million years. And despite being clustered, these stars do not a bound cluster make. Today, all of these stars are expanding away from each other, soon to disperse into the Galactic field.

We next turn to the star-forming region NGC 2264 (see Fig. 13.4), long included in lists of both open clusters and star-forming regions, depending on one's background. The stars are typically 2–5 Myr old. While not an old system, nonetheless it is not as

[2]We note that a more careful estimate of the virial parameter for the region would require an assessment of the density distribution as a function of radius leading to a factor η between 6–11 (e.g. Portegies Zwart et al. 2010) making the region less bound. In addition, potential differences in the velocity dispersion as a function of stellar mass should be considered. A typical approach is to consider a two-mass-bin sample approximation with high-mass stars having a lower velocity dispersion and lower-mass stars having a higher velocity dispersion (e.g. Binney et al. 2008) accounting for possible mass segregation. Even with these complexities in the analysis.

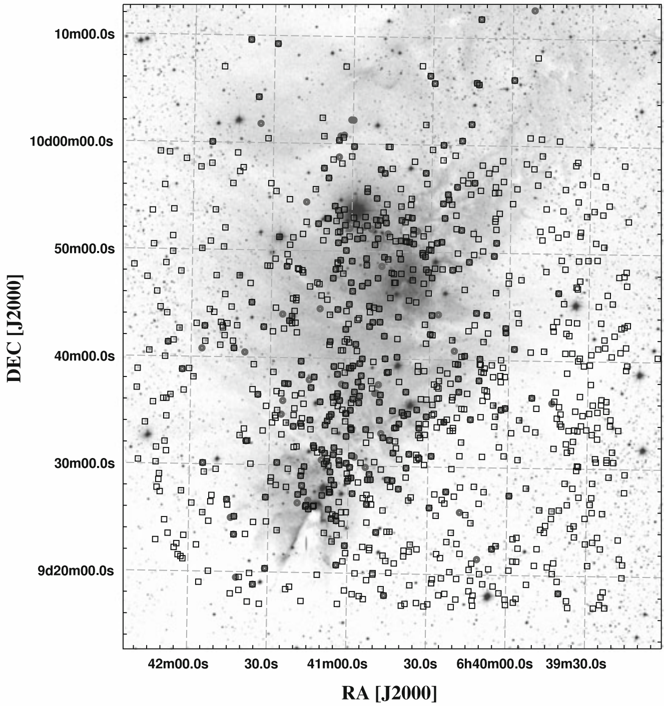

Fig. 13.4 Distribution of NGC 2264 target stars in the radial velocity survey of Fűrész et al. (2006). The *filled circles* are classical T Tauri stars, and show the clumpy and asymmetric spatial structure of the young stars in this star-forming region. Figure from Fűrész et al. (2006)

young as the Orion Trapezium region (although there are still embedded T Tauri stars, so apparently star formation continues). While often called a young open cluster in the literature, even a cursory examination shows the spatial distributions of both the stars and the gas to still be very clumpy, with the stars and gas spatially associated and not dynamically relaxed. The total cluster size is about 8 pc, with two predominant clumps each about 4 pc in radius. Given a velocity dispersion of 1–2 km s^{-1}, the crossing time is 2–4 Myr. As stressed previously, with star-forming regions we are looking at systems with comparable crossing times and ages, and so we should not be surprised that these systems are irregular and not well-mixed.

This dynamical youth can also be seen in the radial velocity distribution for the region (see Fig. 13.5). The essential clues are the asymmetry in the velocity distribution and the unusually large velocity dispersion, $\simeq$3.5 km s^{-1}. More careful examination reveals large-scale systematic trends in the region (see Fig. 13.6). Locally, the typical dispersion is again about 1–2 kms^{-1}. But globally not only do we see spatial organisation but also kinematic organisation across the region (also seen in other regions such as Orion discussed below).

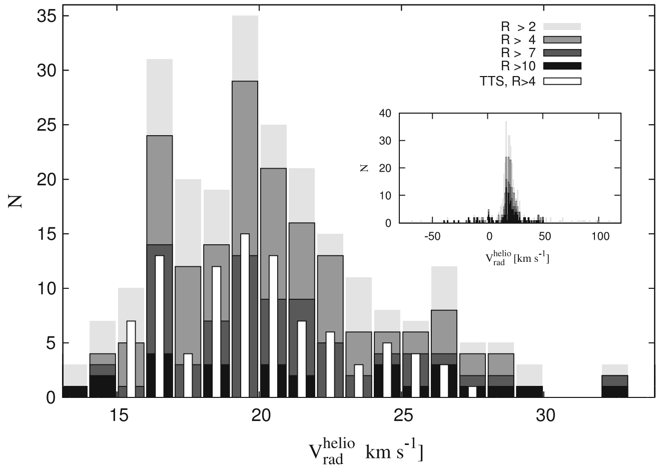

Fig. 13.5 Radial velocity distribution for 344 stars in NGC 2264. The distribution is unusually wide and non-Gaussian. Shading indicates measurement quality, improving with increasing value of R. The white bars show a selection of stars with strong Hα emission, showing little difference between the kinematics of stars with and without active accretion discs. The insert is an expanded velocity range to show how clearly the cluster members form a peak in the velocity space. Figure from Fűrész et al. (2006)

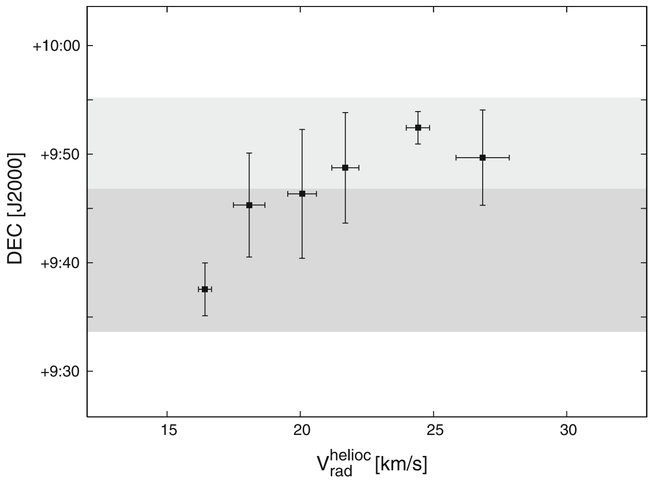

Fig. 13.6 North-south velocity gradient of young stars in NGC 2264, shown by plotting the mean declination values in 2 km s^{-1}-wide radial velocity bins against the mean radial velocity of the bins. The error bars represent the rms of declinations and radial velocities of stars in a given velocity bin. The shaded areas show the declination ranges for the two main condensations of Hα stars. Figure from Fűrész et al. (2006)

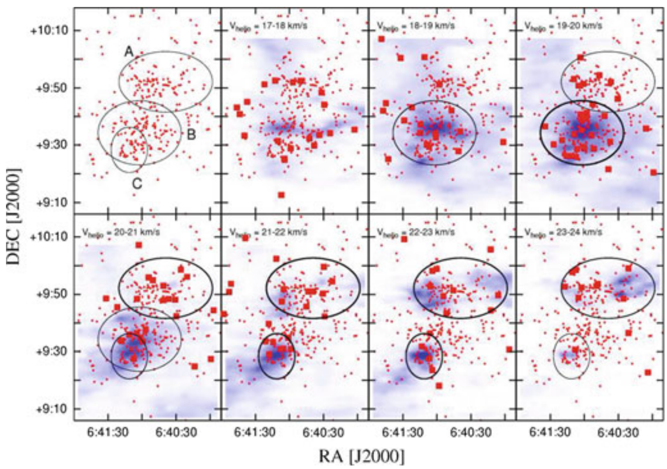

Fig. 13.7 The *red dots* are the Hα-emission stars in the NGC 2264 regions. The *red squares* are young stars with measured radial velocities. The *blue shading* shows the ^{13}CO emission from molecular gas. Three sub-clumps delineated by the molecular emission are identified. Figure from Fűrész et al. (2006)

Figure 13.7 will be familiar to readers who are experts in radio astronomy. It is the equivalent of a channel map. The red dots are the Hα-emission stars in the region, with the red squares being stars with measured radial velocities. The blue shading shows the ^{13}CO emission from molecular gas. The density of red squares tends to correlate with the amount of blue shading in each velocity channel. There is an evident close association of the stars with the gas. But these stars are not embedded in the gas; extinction measurements show that most of the gas is behind the stars, so it is not entirely obvious what is the situation in the third dimension. Perhaps these large structures in the stellar velocity distribution reflect large-scale gradients in the natal molecular cloud.

What can we say about the NGC 2264 star-forming region based on these kinematic studies? First, given a dynamical timescale for the region comparable to the stellar ages, the continued presence of clustering—both spatial and kinematic—of young stars in the region is not surprising given the clumpy gas distribution. Second, the scale of the motions are gravitational. The total mass in this system—gas and stars—is about 4,000 $M_{\odot}$. Given a radius of about 4 pc, we expect motions of 2 km s^{-1}. The gas motions far exceed thermal (see also Clarke Chap. 1) and so are responsive to the gravitational field and pressure. The stars of course do not respond to pressure, and so the close association of gas and stars in both spatial and kinematic dimensions suggests that both are responding in large part to the gravitational potential on a crossing timescale.

13.4 Stellar Kinematics in Young Star Clusters

For the purposes of studying the kinematics in young star clusters, we will choose the Orion region as our case study. If one peruses the literature, however, one finds reference to the Trapezium Cluster, the Orion Nebula Cluster and the Orion Nebula region, all centred on the Trapezium stars but with different extents. Why? Because nature does not provide clear demarcations around the structures in star-forming regions, and it is not evident where are the boundaries of the ever larger stellar systems around the Trapezium OB stars.

In any case, the size-scale of the stellar clustering in this region is around 2 pc diameter. Again for a rough estimate, if we adopt a 2 km s^{-1} velocity dispersion, we find a crossing time of a couple Myr. The oldest stars in these regions have a derived age of about 2 Myr, with most stars being much younger.[3] It is likely that few stars have completed more than one orbit in the local gravitational potential. In addition, the stellar distribution shows significant structure, especially being elongated in the north-south direction.

In 1988 two excellent proper motion studies of this region were published, one of very-high precision (van Altena et al. 1988) and one covering a wider field at excellent precision (Jones and Walker 1988). van Altena et al. (1988) measured a one-dimensional velocity dispersion of 1.5 km s^{-1} for the core of the region. Jones and Walker (1988) found a velocity dispersion of 2.5 km s^{-1}, possibly with some anisotropy further from the core and some mass dependence. But perhaps most importantly, they make the dynamical argument that, 'On the basis of the velocity dispersion, and the stellar and gas masses, we conclude that we are not seeing a protocluster but a system in disruption.'[4]. This statement was based on a global analysis; it remains unclear whether the core of the region (the so-called Trapezium Cluster) is unbound. Nonetheless, the words of Jones and Walker were prescient in recognising that clusterings of young stars were not necessarily destined to be open clusters.

More recently, this region has been the subject of a wide-field, high-precision radial velocity study (Tobin et al. 2009; see also Fűrész et al. 2008). Again, the region shows structure in the stellar spatial and velocity distributions. Figure 13.8 shows a position-velocity diagram for the region. The mode of the stellar velocity distribution at each declination is delineated by the blue line, superimposed upon the ^{13}CO distribution. The spatial extent of Fig. 13.8 is 16 pc, and the location of

[3]There are some that appear to be much older, which is somewhat confusing—perhaps they are part of the Orion 1C association that is projected in front of it. Alternatively, we may not understand the ages of pre-main-sequence stars as well as we hope.

[4]As a technical aside, historically many of the proper motion studies of the Trapezium region focused on detection of expansion. Classically this was difficult in measuring proper motions from plates, for the slightest differences in plate scale would mimic systemic radial motions (or alternatively, an expansion term was a parameter determined from the stars on the plates). Thus neither of these more modern studies spoke to the expansion of the cluster. With a well-determined independent frame of reference, *Gaia* should finally accomplish the goal of the first astrometrists who studied this star-forming region.

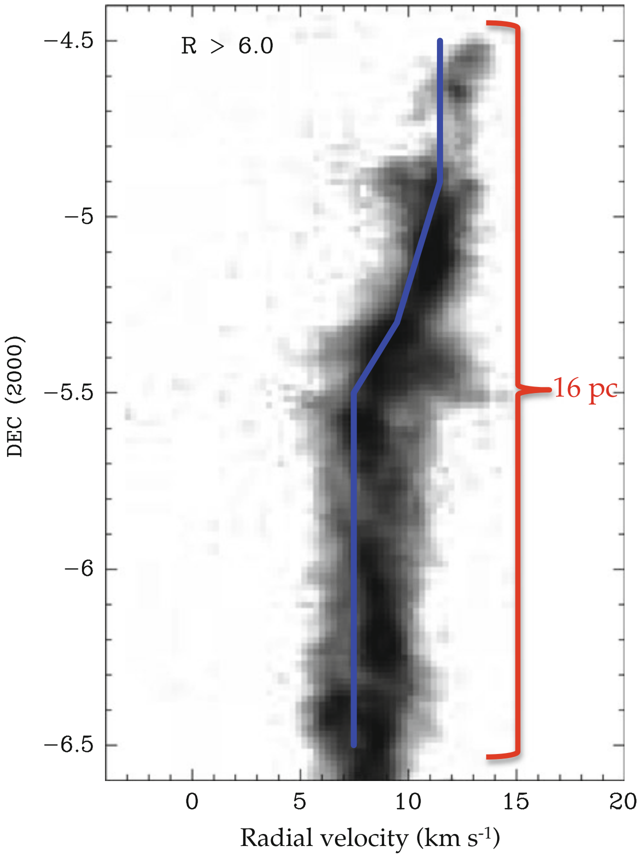

Fig. 13.8 Position-velocity diagram for stars and ^{13}CO molecular gas emission around the Trapezium. The *blue line* represents the mode of the stellar velocity distribution for kinematic members at each declination. Figure adapted from Tobin et al. (2009)

the Trapezium is shown. Most notable is the significant systemic velocity shift of the stellar velocities, following the north-south ridge of moderate-density molecular gas in this region. Specifically there is a 2.5 $\mathrm{km\,s^{-1}}$ shift over a scale of only 2 pc or so, compared to the 16 pc extent of the entire region shown in Fig. 13.8. Equally importantly, the kinematics of the stars follows that of the gas. Finally, this gradient happens very near to the Trapezium and the associated clustering of stars.

Thus, as with NGC 2264, the scale of the systematic signatures in the velocities suggest on-going gravitational effects. Tobin et al. (2009) and Proszkow et al. (2009) use these data in an attempt to back out the initial conditions of the cluster formation. These authors argue that the systematic velocity shift is the result of infall of an elongated, sub-virial, collapsing filament associated with the formation of the Trapezium cluster. Whether this interpretation is correct or not is perhaps not the key point; we are very early in the game. Many of us remember the ambiguities and multiple interpretations in the study of molecular line widths as we tried to understand whether clouds were rotating or collapsing. More important is that in terms of the internal kinematics of star-forming regions, we are entering into the domain of detailed kinematic maps as compared to simply velocity dispersions. *Gaia* observations combined with sub-km s^{-1} precision radial velocities will soon allow us to examine in detail the systematic flows within star-forming regions driven by gravity and internal motions.

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