17 Star Clusters and Associations

Several collections of stars can be picked out in the sky, even with the naked eye. Closer study reveals that they really do form separate clusters in space. E.g. the Pleiades in Taurus and the Hyades around Aldebaran, the brightest star in Taurus, are such *open star clusters*. Almost the whole of the constellation Coma Berenices is also an open star cluster. Many objects appearing as nebulous patches to the unaided eye, when looked at with a telescope, turn out to be star clusters, like Praesepe in the constellation Cancer, or double cluster in Perseus (Fig. 17.1). In addition to open clusters some apparently nebulous objects are very dense *globular clusters*, such as those in Hercules and in Canes Venatici (Fig. 17.2).

The first catalogue of star clusters was prepared by the French astronomer *Charles Messier* in 1784. The first version contained only 45 objects, but later Messier himself and Pierre Méchain expanded the catalogue to include 103 objects. Later seven more objects were added, possibly observed by Messier. Messier was interested in comets, not in those fuzzy objects, and the reason for the catalogue was to avoid false alarms. The catalogue contains a mixture of very different objects, like about 30 globular clusters and the same number of open clusters, gas nebulae and galaxies.

A larger catalogue, published in 1888, was the *New General Catalogue of Nebulae and Clusters of Stars* prepared by the Danish astronomer *John Louis Emil Dreyer*. The catalogue numbers of objects in this list are preceded by the initials NGC. For example, the large globular cluster in Hercules is object M13 in the Messier catalogue, and it is also known as NGC 6205. The NGC catalogue was supplemented with the *Index Catalogue* in 1895 and 1910. The objects of this catalogue are given the initials IC.

With a small telescope stars of distant clusters and galaxies cannot be distinguished as separate objects; instead the target looks nebulous. Therefore their true nature was only little by little with spectroscopy and large telescopes. That's why those old catalogues contain all kinds of different objects.

Even now there is no catalogue of open cluster complete to some limiting magnitude. The data are collected from several catalogues published by various astronomers, and therefore the nomenclature is not consistent. The problem is that open clusters concentrate close the plane of Milky Way, and there are a lot of background stars. Thus identifying the cluster members may require rather detailed studies of the properties of the stars. Also the members may already have dispersed to a very wide area making it difficult to decide which of them belong to the same cluster.

17.1 Associations

In 1947 the Soviet astronomer *Viktor Amazaspovich Ambartsumyan* discovered that there are groups of young stars scattered over so large regions of the sky that they would be very difficult to identify merely on the basis of their appearance. These *associations* may have a few tens of

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members. One association is found around the star ζ Persei, and in the region of Orion, there are several associations.

Associations are groups of very young stars. They are usually identified on the basis either of absolutely bright main sequence stars or of T Tauri stars. According to the type, one speaks of OB associations and T Tauri associations. The most massive stars of spectral class O stay on the main sequence for only a few million years, and therefore associations containing them are necessarily young. The T Tauri stars are even younger stars that are in the process of contracting towards the main sequence.

Studies of the internal motions in associations show that they are rapidly dispersing. There are so few stars in an association that their gravity cannot hold them together for any length of time. The observed motions have often confirmed that the stars in an association were very close together a few million years ago (Fig. 17.3).

Large amounts of interstellar matter, gas and dust nebulae often occur in connection with associations, supplying information about the connection between star formation and the interstellar medium. Infrared observations have shown that stars are now forming or have recently formed in many dense interstellar clouds.

Associations are strongly concentrated in the spiral arms in the plane of the Milky Way. Both in the Orion region and in the direction of Cepheus, three generations of associations have been iden-

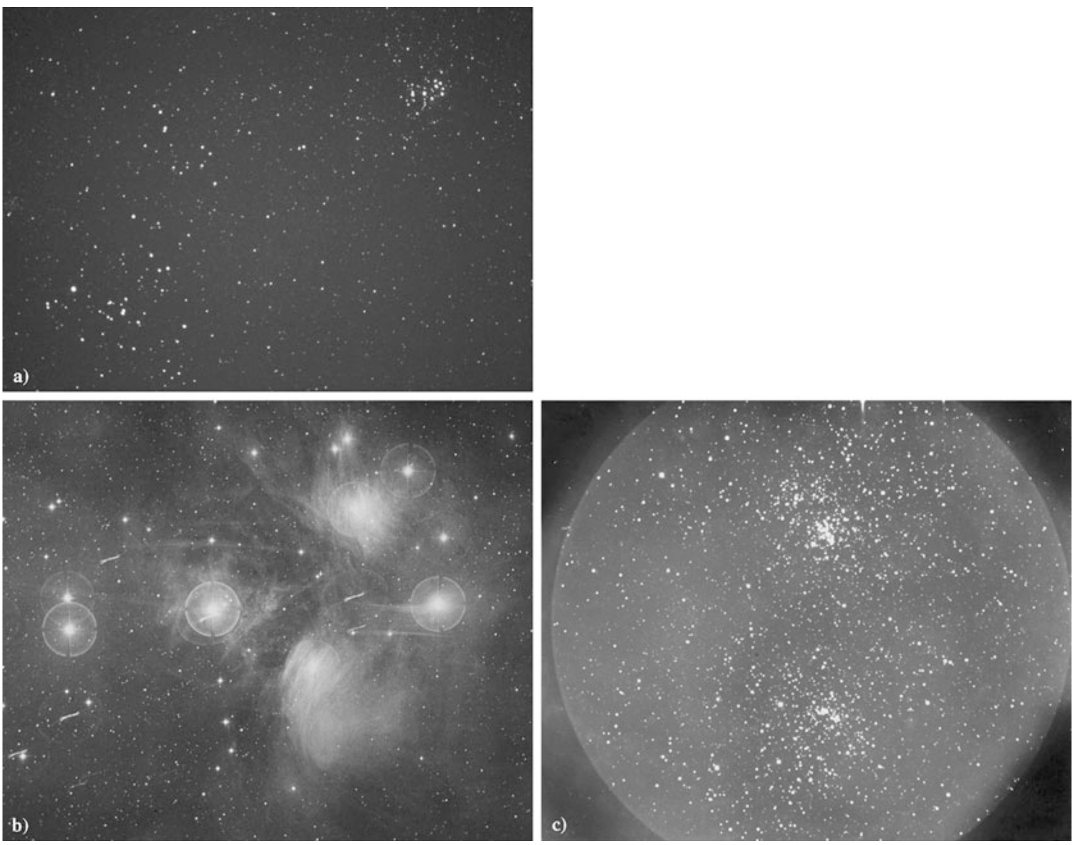

Fig. 17.1 Open clusters. (**a**) The Hyades slightly to the lower left in the photograph. Above them to the right the Pleiades. (Photograph M. Korpi.) (**b**) The Pleiades photographed with the Metsähovi Schmidt camera. The diameter of the cluster is about 1°. Reflection nebulae are visible around some of the stars. (Photograph M. Poutanen and H. Virtanen, Helsinki University.) h and χ Persei, the double cluster in Perseus. The separation between the clusters is about 25′. Picture taken with the Metsähovi 60-cm Ritchey Chrétien telescope. (Photograph T. Markkanen, Helsinki University)

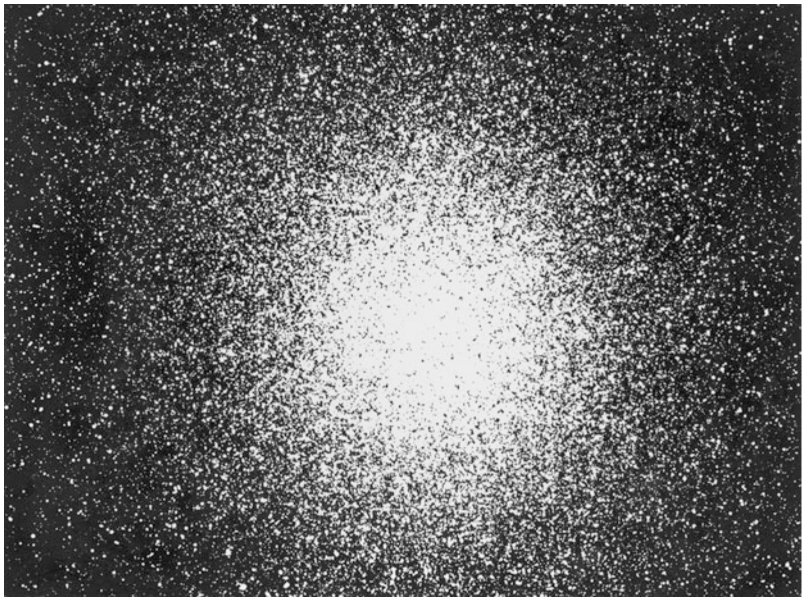

Fig. 17.2 The globular cluster ω Centauri. The picture was taken with the Danish 1.5-m telescope at La Silla, Chile. Thanks to the excellent seeing, one can see through the entire cluster in some places. (Photograph T. Korhonen, Turku University)

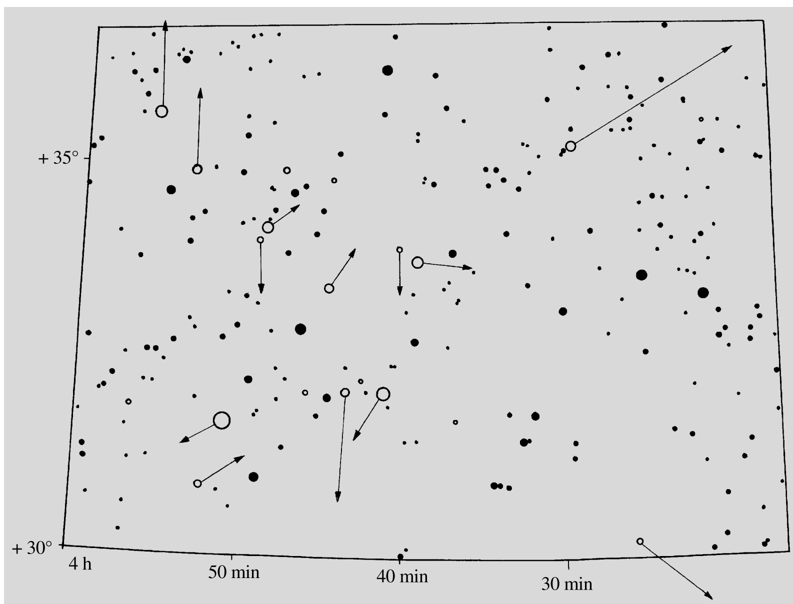

Fig. 17.3 ζ Persei association. O and B stars are shown as *open circles*. The proper motion *vectors* show the movements of the stars in the next 500,000 years

tified, the oldest ones being most extended and the youngest ones, most dense.

17.2 Open Star Clusters

Open clusters usually contain from a few tens to a few hundreds of stars. The kinetic energy of the cluster members, the differential rotation of the Milky Way (Sect. 17.3) and external gravitational disturbances tend to gradually disperse the open clusters. Still, many of them are fairly permanent; for example, the Pleiades is many hundreds of millions of years old, but nevertheless, quite a dense cluster.

The distances of star clusters—and also of associations—can be obtained from the photometric or spectroscopic distances of their brightest members. For the nearest clusters, in particular for the Hyades, one can use the method of *kinematic parallaxes*, which is based on the fact that the stars in a cluster all have the same average space velocity with respect to the Sun. The proper motions in the Hyades are shown in Fig. 17.4. They all appear to be directed to the same point. Figure 17.5 explains how this convergence can be understood as an effect of perspective, if all cluster members have the same velocity vector with respect to the observer. Let θ be the angular distance of a given star from the convergence point. The angle between the velocity of the star and the line of sight will then also be θ. The velocity components along the line of sight and at right angles to it, v_r and v_t, are therefore given by

$$v_r = v\cos\theta, \quad v_t = v\sin\theta. \tag{17.1}$$

The radial velocity v_r can be measured from the Doppler shift of the stellar spectrum. The tangential velocity v_t is related to the proper motion μ and the distance r:

$$v_t = \mu r. \tag{17.2}$$

Thus the distance can be calculated:

$$r = \frac{v_t}{\mu} = \frac{v\sin\theta}{\mu} = \frac{v_r}{\mu}\tan\theta. \tag{17.3}$$

By means of this method, the distances of the individual stars can be determined from the motion of the cluster as a whole. Since the method of (ground-based) trigonometric parallaxes is reliable only out to a distance of 30 pc, the moving cluster method is an indispensable way of determining stellar distances. The distance of the Hyades obtained in this way is about 40 pc. The distance obtained from the trigonometric parallaxes measured directly by the Hipparcos satellite in the 1990's is 46 pc. The Hyades is the nearest open cluster.

The observed HR diagram or the corresponding colour–magnitude diagram of the Hyades and other nearby star clusters show a very well-defined and narrow main sequence (Fig. 17.6). Most of the cluster members are main sequence stars; there are only a few giants. There are quite a few stars slightly less than one magnitude above the main sequence. These are apparently binary stars whose components have not been resolved. To see this, let us consider a binary, where both components have the same magnitude m and the same colour index. If this system is unresolved, the colour index will still be the same, but the observed magnitude will be $m - 0.75$, i.e. slightly less than one magnitude brighter.

The main sequences of open clusters are generally located in the same section of the HR or colour-magnitude diagram (Fig. 17.7). This is because the material from which the clusters formed

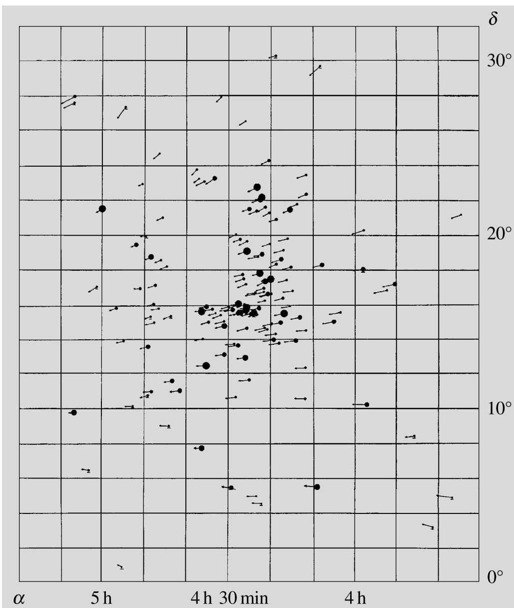

Fig. 17.4 Proper motions of the Hyades. *The vectors* show the movement of the stars in about 10,000 years. (van Bueren, H.G. (1952): Bull. Astr. Inst. Neth. **11**)

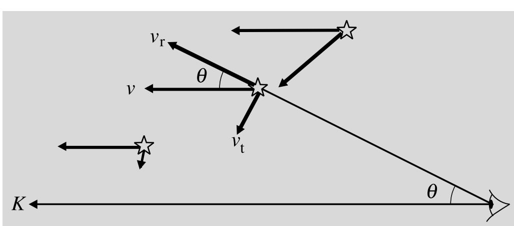

Fig. 17.5 If all stars move in the same direction, their tangential velocity components appear to be directed towards the convergence point K

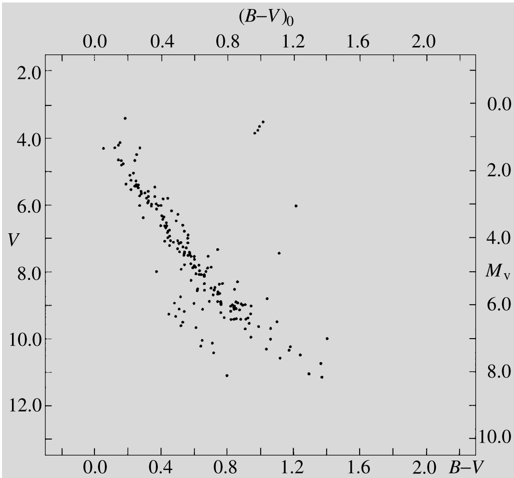

Fig. 17.6 Colour–magnitude diagram of the Hyades. Apparent visual magnitude on *the left-hand vertical axis*; absolute visual magnitude on *the right-hand one*

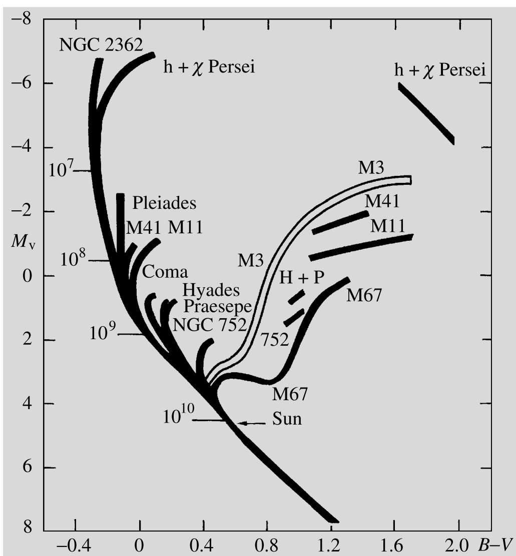

Fig. 17.7 Schematic colour–magnitude diagrams of star clusters. M3 is a globular cluster; the others are open clusters. Cluster ages are shown along the main sequence. The age of a cluster can be told from the point where its stars begin to turn off the main sequence. (Sandage, A. (1956): Publ. Astron. Soc. Pac. **68**, 498)

has not varied much, i.e. their initial chemical composition has been fairly constant. In younger clusters the main sequence extends to brighter and hotter stars and earlier spectral types. Usually one can clearly see the point in the diagram where the main sequence ends and bends over towards the giant branch. This point will depend very strongly on the age of the cluster. It can therefore be used in determining the ages of open clusters. Star clusters are of central importance in the study of stellar evolution.

The colour–magnitude diagrams of star clusters can also be used to determine their distances. The method is called *main sequence fitting*. By means of multicolour photometry the reddening due to interstellar dust can be removed from the observed colours $B-V$ of the stars, yielding the intrinsic colours $(B-V)_0$. Most star clusters are so far away from us that all cluster members can be taken to be at the same distance. The distance modulus

$$m_{V_0} - M_V = 5 \lg \frac{r}{10\ \text{pc}} \qquad (17.4)$$

will then be the same for all members. In (17.4), m_{V_0} is the apparent, M_V the absolute visual magnitude of a star, and r the distance. It has been assumed that the extinction due to interstellar dust A_V has been determined from multicolour photometry and its effect removed from the observed visual magnitude m_V:

$$m_{V_0} = m_V - A_V .$$

When the observed colour–magnitude diagram of the cluster is plotted using the apparent magnitude m_{V_0} rather than the absolute magnitude M_V on the vertical axis, the only change will be that the position of the main sequence is shifted vertically by an amount corresponding to the distance modulus. The observed $(m_{V_0}, (B-V)_0)$ diagram may now be compared with the Hyades $(M_V, (B-V)_0)$ diagram used as a standard. By demanding that the main sequences of the two diagrams agree, the distance modulus and hence the distance can be determined. The method is very accurate and efficient. It can be used to determine cluster distances out to many kiloparsecs.

17.3 Globular Star Clusters

Globular star clusters usually contain about 10^5 stars. The distribution of the stars is spherically symmetric, and the central densities are about ten times larger than in open clusters. Stars in globular clusters are among the oldest in the Milky Way, and therefore they are of great importance for studies of stellar evolution. There are about 150–200 globular clusters in the Milky Way.

The colour-magnitude diagram of a typical globular cluster is shown in Fig. 17.8. The main sequence only contains faint red stars; there is a prominent giant branch, and the horizontal and asymptotic branches are clearly seen. The main sequence is lower than that of the open clusters, because the metal abundance is much lower in the globular clusters.

The horizontal branch stars have a known absolute magnitude, which has been calibrated using principally RR Lyrae type variables. Because the horizontal branch stars are bright, they can be observed even in distant clusters, and thus using them the distances of globular clusters can be well determined.

Using the known distances, the linear sizes of globular clusters can be calculated. It is found that most of the mass is concentrated to a central core with a radius of about 0.3–10 pc. Outside this there is an extended envelope with a radius that may be 10–100 times larger. At even larger radii stars will escape from the cluster because of the tidal force of the Galaxy.

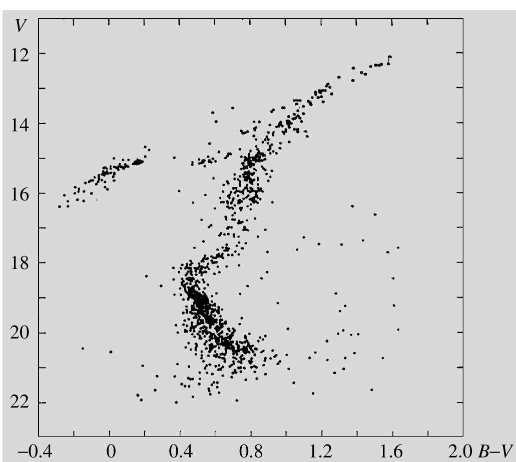

Fig. 17.8 Colour–magnitude diagram of the globular cluster M5. In addition to the main sequence one can see the giant branch bending to the right and to its left the horizontal brunch. (Arp, H. (1962): Astrophys. J. **135**, 311)

The masses of globular clusters can be roughly estimated from the virial theorem, if the stellar velocities in the cluster have been measured. More precise values are calculated by fitting theoretical models to the observed density and velocity distributions. In this way masses in the range 10^4–$10^6\,M_\odot$ have been obtained.

The globular clusters in the Milky Way fall into two classes. In the classification given in Table 18.1 these correspond to intermediate and halo population II. The disk globular clusters are concentrated towards the centre and the plane of the Milky Way and they form a system that is rotating with the general rotation of the Milky Way. In contrast, the halo clusters are almost spherically distributed in an extensive distribution reaching out to at least 35 kpc. The system of halo clusters does not rotate, but instead the velocities of individual clusters are uniformly distributed in all directions. The abundance of heavy elements is also different in the two classes of clusters. For disk clusters it is typically about 30 % of the solar value, for halo clusters it is only about 1 %. In some clusters the heavy element abundances are only 10^{-3} times the solar value. The smallest values, as low as 10^{-4}–10^{-5} have been detected in some field stars of the halo. They therefore give important information about the production of elements in the early Universe and during the formation of the Milky Way.

All globular clusters are old, and the halo clusters are among the oldest known astronomical objects. Determining a precise age is difficult, and requires both accurate observations of the turnoff point of the main sequence in the HR diagram, as well detailed theoretical stellar evolution models. The ages obtained have been about 13×10^9 years. This age is close to the age of the Universe calculated from its rate of expansion (see Chap. 20).

17.4 Example

Example 17.1 Assume that a globular cluster has a diameter of 40 pc and contains 100,000 stars of one solar mass each.

(a) Use the virial theorem to find the average velocity of the stars. You can assume that the average distance between stars equals the radius of the cluster.

(b) Find the escape velocity.

(c) Comparing these velocities, can you tell something about the stability of the cluster?

(a) First, we have to estimate the potential energy. There are $n(n-1)/2 \approx n^2/2$ pairs of stars in the cluster, and the average distance of each pair is R. Thus the potential energy is about

$$U = -G\frac{m^2}{R}\frac{n^2}{2},$$

where $m = 1\,M_\odot$. The kinetic energy is

$$T = \frac{1}{2}mv^2 n,$$

where v is the root mean square velocity. According to the virial theorem we have $T = -1/2U$, whence

$$\frac{1}{2}mv^2 n = \frac{1}{2}G\frac{m^2}{R}\frac{n^2}{2}.$$

Solving for the velocity we get

$$\begin{aligned} v^2 &= \frac{Gmn}{2R} \\ &= \frac{6.7\times10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}\times2.0\times10^{30}\ \mathrm{kg}\times10^5}{40\times3.1\times10^{16}\ \mathrm{m}} \\ &= 1.1\times10^7\ \mathrm{m^2\,s^{-2}}, \end{aligned}$$

which gives $v \approx 3\ \mathrm{km\,s^{-1}}$.

(b) The escape velocity from the edge of the cluster is

$$\begin{aligned} v_\mathrm{e} &= \sqrt{\frac{2Gmn}{R}} \\ &= \sqrt{4v^2} = 2v = 6\ \mathrm{km\,s^{-1}}. \end{aligned}$$

(c) No. The average velocity seems to be smaller than the escape velocity, but it was derived from the virial theorem assuming that the cluster is stable.

17.5 Exercises

Exercise 17.1 A globular cluster consists of 100,000 stars of the solar absolute magnitude. Calculate the total apparent magnitude of the cluster, if its distance is 10 kpc.

Exercise 17.2 If the apparent magnitude of the cluster of the previous exercise is 10, what is its distance if the interstellar absorption in the direction of the cluster is 1.5 mag/kpc?

Exercise 17.3 The Pleiades open cluster contains 230 stars within 4 pc. Estimate the velocities of the stars in the cluster using the virial theorem. For simplicity, let the mass of each star be replaced by $1\,M_\odot$.