RUNAWAY STARS AND THE FORCE PERPENDICULAR TO THE GALACTIC PLANE

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ABSTRACT

Motions of 32 Hipparcos stars with distances from the galactic plane between 400 and 3000 pc, ages less than 80 Myr and with known radial velocities have been studied. Of 25 stars younger than 40 Myr, 24 move out from the plane with velocity components perpendicular to the plane between 0 and 150 km/s. Obviously, these stars are runaway stars born in the galactic plane that have not yet reached their maximum distance from the plane.

Assuming that the ejection from the plane took place soon after the birth of the star, the time it has taken the star to reach its distance from the plane must be close to the age of the star. The knowledge of the distance from the plane, the velocity at that distance and the time it has taken to reach that distance contains information about the gravitational force component perpendicular to the plane.

This scheme complements the classical statistical methods for determining K_z to larger values of Z.

The suitability of this method to determine the force perpendicular to the galactic plane, and thereby the projected surface density in the plane, is discussed. Such considerations may also have implications concerning the nature of the runaway star phenomenon.

Key words: runaway stars; galactic potential.

1. SELECTION AND CALIBRATIONS

For a study of the kinematics of young stars in the solar neighbourhood as a function of space distribution and age we selected those stars in the Hipparcos Input Catalogue for which complete Strömgren u, v, b, y and $H\beta$ photometry was available and that belong to Strömgren's 'early group' (Strömgren 1966; Westin 1985). The photometry was corrected for interstellar reddening following Shobbrook (1983). Absolute visual magnitudes M_V were computed using relations by Balona & Shobbrook (1984). Distances were derived from M_V and the V magnitudes given in the Hipparcos Catalogue as well as effective temperatures and bolometric corrections according to the scheme for early group stars given by Balona (1994). Ages of the stars were then determined by interpolation in the tables of star models by Maeder & Meynet (1988).

Supergiants were excluded because the reddening corrections applied will not be accurate. Also excluded were stars where the possible variation in the Hipparcos magnitude system $Hp > 0.6$ mag, the magnitude difference between components $\Delta Hp < 1.23$ mag, error in proper motion > 2 mas/yr, error in radial velocity > 20 km/s, relative error in distance > 0.3 and error in age determination > 20 Myr.

2. KINEMATICS OF HIGH VELOCITY STARS

Figure 1 shows the velocity component perpendicular to the galactic plane, corrected for solar motion, W_{LSR}, versus the distance from the plane, Z, for all stars in our sample younger than 80 Myr for which radial velocities were available. The preference of two quadrants in this figure shows that practically all young stars with high W velocity or large distance from the plane move outwards from the plane. As high velocities towards the plane only occur at very small Z, these stars must have been ejected from the immediate vicinity, i.e. within some 100 pc, of the plane. We will here call them 'runaway' stars even if they are not 'bona fide' runaways as defined by Blaauw (1993). The origin of runaway stars has been suggested to be either a massive binary where one component exploded as a supernova (Blaauw 1961) or ejection from a stellar cluster (Poveda et al. 1967).

We also note that few of these young stars have had time to begin their return to the plane. In Figure 2 we see the distribution of outward velocities as a function of age for the 32 stars in our sample with $|Z| > 400$ pc. From this figure we see that very few observable stars of age < 40 Myr have reached their maximum distance from the plane. Before drawing conclusions about the decelerating force perpendicular to the plane from the change of the velocity distribution with age, one must be aware that the population of stars observed changes with age in the

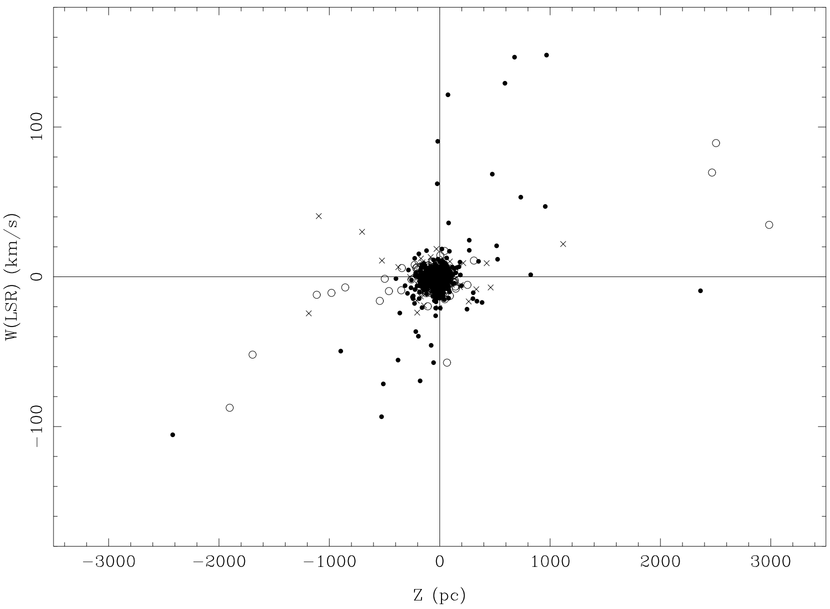

Figure 1. Velocity component perpendicular to the galactic plane as a function of distance from the plane for 834 stars younger than 80 Myr. Ages for the stars are indicated by black dots (< 20 Myr), open circles (20 − 40 Myr) or crosses (40 − 80 Myr).

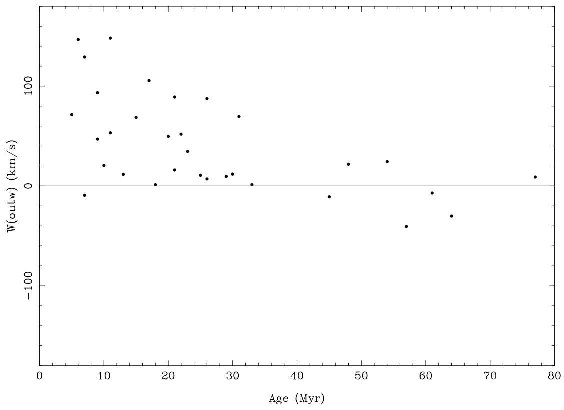

Figure 2. Velocity out from the galactic plane as a function of age for 32 stars with distance from the plane |Z| > 400 pc. (Negative outgoing velocity means velocity towards the galactic plane.)

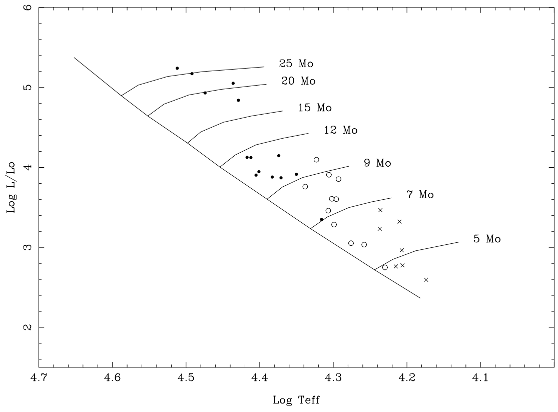

Figure 3. HR diagram for the 32 young runaway stars. Evolutionary tracks and masses are from Maeder & Meynet (1988). Ages for the stars are indicated by black dots (< 20 Myr), open circles (20 − 40 Myr) or crosses (40 − 80 Myr).

sense that young stars in the figure do not evolve to the older stars.

In Figure 3 the HR diagram for the 32 stars is displayed with the evolutionary tracks and masses for normal stars superimposed. As is seen there is a strong correlation between age and mass. When the young stars evolve they disappear from our sample. The older stars are intrinsically fainter and may not so easily be observed to large distances from the galactic plane.

Now consider the individual stars. If the star is leaving the galactic plane shortly after its birth, then the time it has taken the star to reach the distance Z over the plane must be close to the age of the star. It is evident that the knowledge of the distance from the plane, the velocity at that distance, and the time it has taken to reach that distance must contain information about the gravitational force component perpendicular to the plane.

To extract this information, it would be necessary to integrate the vertical orbit of the star with boundary conditions in the plane and at the observed position. To illustrate the case and still avoid complicated integrations let us assume as a first approximation that the force per unit mass perpendicular to the plane, $K_{\rm z}$, is constant and independent of the distance Z to the plane – a law that is valid outside an infinitely large homogeneous disk.

For observed Z, vertical velocity W, and age A, as Z/A is the mean velocity, we then have:

$$K_{\rm z} = 2\,\frac{W - Z/A}{A} \tag{1}$$

In Figure 4 $K_{\rm z}$ as derived from Equation (1) is plotted versus age and in Figure 5 versus the absolute value of the time average of Z up to the present moment, where, in our approximation, this time average is given by:

$$Z_{\rm mean} = \frac{Z}{2} + \frac{1}{6}\,(Z - WA) \tag{2}$$

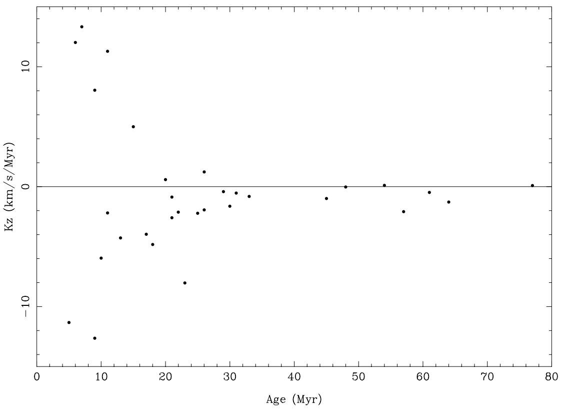

Figure 4. Force perpendicular to the galactic plane calculated from Equation (1) as a function of age for the runaway stars.

We see that for ages less than about 20 Myr the scatter is large, giving even high positive values for $K_{\rm z}$, while for higher ages the stars seem to gather around moderate negative values. There are several reasons for this large scatter for the youngest stars. The expression above for $K_{\rm z}$ contains the square of the age in the denominator. Over their lifetime young stars may not have acquired a difference between present velocity and mean velocity which is sufficiently large compared to the error in the velocity determination. Further, for all stars that have spent most of their lives at low Z the relative error of the distance travelled may be large because the stars are not ejected exactly in the galactic plane.

In Figure 5 the full drawn line gives the force $K_{\rm z}$ as a function of Z from Bahcall (1984, Figure 7) as derived from statistics of space and velocity distributions of K giants. The fair agreement with our results for stars older than 20 Myr and $Z > 500$ pc, in spite of the approximations applied here, gives hope that the method suggested to derive $K_{\rm z}$ might work for stars in the age interval $20 - 80$ Myr.

3. DISCUSSION

The applicability of this scheme depends entirely on the two assumptions:

- ages for these young runaway stars can be determined with sufficient accuracy and
- this age is equal to the time elapsed since the star was ejected from the galactic plane.

If the runaway stars are remnants of massive binaries that have evolved with mass exchange, as in the supernova ejection model (see van den Heuvel 1994), the stellar evolution will be more complicated than assumed here. On the other hand, Blaauw (1993) has shown that very recently ejected runaway stars appear as blue stragglers close to the zero age main sequence as compared with the parent association. Mass transfer has rejuvinated the mass-receiving component. This in turn may take us back to the simpler evolutionary models after the ejection and help to make the two assumptions valid in the supernova ejection picture. Still, the circumstance that the atmosphere will be enriched by helium and eventually other elements (Blaauw 1993) should be taken into consideration.

With the cluster ejection mechanism the second assumption may be violated. According to Leonard & Duncan (1990) the most efficient clusters at producing collisions between very hard initial binaries are expected to produce, on average, one runaway star within typically 20 Myr. The time delay between creation of the star and ejection may thus not be short compared to the age of the star.

As can be seen in Figure 3, stars of ages $20 - 70$ Myr have masses of $5 - 10$ $M_\odot$. Stars with ages smaller than 20 Myr will have masses larger than 10 $M_\odot$. It cannot be excluded that different physical scenarios may be at work within different mass intervals.

As seen in Figure 5, the force $K_{\rm z}$ flattens out at a value of 2.0 km s^{-1} Myr^{-1} for $Z > 500$ pc. This is actually closely equal to the slope of the upper limit of the velocity distribution in Figure 2. A question that comes up is whether this means that the initial velocity distribution at right angles to the galactic plane is independent of mass for the runaway stars.

If the assumptions behind this approach are valid, the scheme presented would complement the classical statistical methods for determining $K_{\rm z}$ to larger values of Z and in particular estimate its eventual limiting value at large Z. In addition it could also throw light on the nature of runaway stars.

4. FUTURE NEEDS

In order to improve this method and test its usefulness, theoretically based age determination taking into account an evolution involving mass exchange of interacting binaries resulting in supernova explosions and the enrichment of the atmosphere of helium and other elements should be applied.

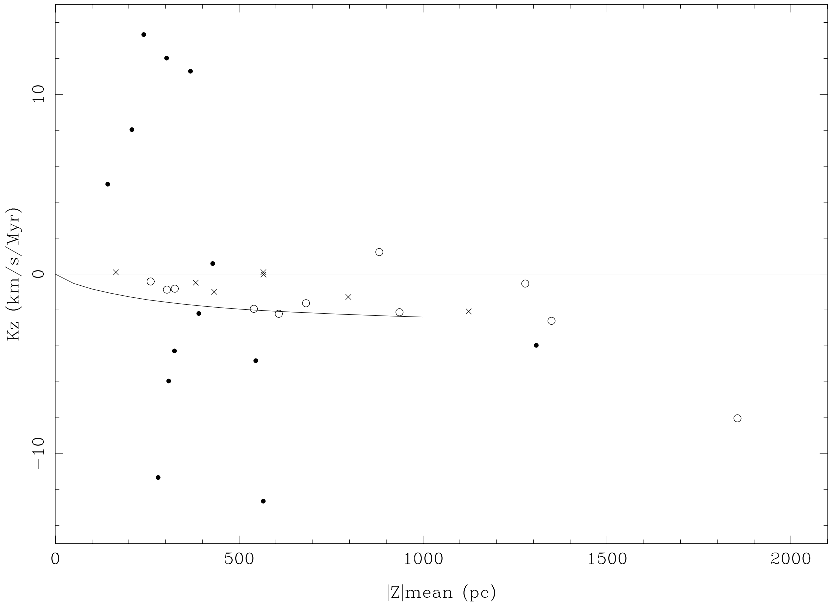

Figure 5. Force perpendicular to the galactic plane calculated by Equation (1) as a function of mean distance from the plane for the runaway stars. Ages for the stars are indicated by black dots (< 20 Myr), open circles (20 − 40 Myr) or crosses (40 − 80 Myr). The solid line is the relation for the force given by Bahcall (1984, Figure 7) for a model that fits the Oort (1960) K giant density distribution.

Integrations of orbits in more realistic models of the dependence of the force K_z on the distance from the galactic plane must be applied.

Finally, dedicated observations of radial velocities of candidate stars, as well as photometric calibrations of supergiant stars, would significantly increase the sample of Hipparcos stars suitable for this purpose.

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