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# The Close Approach of Stars in the Solar Neighbourhood

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## SUMMARY

We examine the kinematics of stars in the Solar Neighbourhood, and compute their trajectories and distances of closest approach to the Sun. We find that Proxima has been the closest star to the Sun for the last 32000 years, but will lose this status to the dwarf star Ross 248 in 33000 years. We are approaching a period relatively rich in stellar encounters, with six stars all coming closer to the Sun than the current distance of Proxima Centauri over the next 45000 years. Only the close approach of α Cen A/B will have any detectable dynamical effect, however, perturbing the outer Oort Cloud and putting about $10^5$ comets into potentially Earth-impacting orbits.

## 1 INTRODUCTION

The Solar Neighbourhood may be defined as the region of interstellar space centred on the Sun whose contents are known with reasonable completeness, i.e. a volume with a radius of about 5 pc (Gilmore 1992).

At present, 58 stars are known to lie within this distance of the Sun (Zombeck 1990). In this paper we use current data for the parallax, proper motion and radial velocity of stars in the Solar Neighbourhood to compute their past and future trajectories.

This allows us to investigate the kinematic past, present and future of Proxima, which at $1{\cdot}295 \pm 0{\cdot}007$ pc is currently the closest star to the Sun (Kamper & Wesselink 1978). It emerges that, despite its proximity, considerable uncertainty still surrounds some basic features of this star's motion in space.

The vast majority of stars in the Solar Neighbourhood are smaller than the Sun, and even at their closest approach they will have a negligible dynamical effect on the Solar System. However, the relatively massive binary system α Cen A/B appears to be an exception, and we examine the extent of disruption of the Oort Cloud caused by its close approach.

We begin with a brief summary of the theory underlying our conclusions.

## 2 STELLAR KINEMATICS

A star, now at a distance of $d_0$ pc from the Sun, will typically have a space velocity $v_s$ relative to the Sun. This velocity can be resolved into three orthogonal components: a radial velocity along the line of sight, $R_v$, and two tangential components in the directions of increasing right ascension and declination. The resultant of the latter two is the proper motion, denoted by $\mu$, and expressed in seconds of arc per year (arcsec/yr). It is easily shown that the corresponding tangential velocity is

$$v_t\,[\text{km/sec}] = 4{\cdot}74(d_0\,[\text{pc}] \times \mu[\text{arcsec/yr}]). \qquad (1)$$

The total space velocity, $v_s$, is then

$$v_s = (R_v{}^2 + v_t{}^2)^{1/2}. \tag{2}$$

The distance of a star from the Sun at any given time $t$ follows from the cosine rule:

$$d(t)^2 = d_0{}^2 - (2d_0\, v_s \cos\phi)\, t + (v_s{}^2)\, t^2 \tag{3}$$

where

$$\phi = \arctan(v_t/R_v). \tag{4}$$

Simple geometry also shows that the closest approach distance of the star is given by

$$d_c = d_0 \sin\phi = d_0/\{1 + (R_v/v_t)^2\}^{1/2} \tag{5}$$

and the time to this closest approach, measured from the current epoch, is

$$t_c = d_0 \cos\phi/v_s = d_0\, R_v/\{v_t{}^2 + R_v{}^2\} \tag{6}$$

which leads to

$$t_c\,[\mathrm{yrs}] = 9{\cdot}78 \,.\, 10^5\, (d_0\,[\mathrm{pc}] \cos\phi/v_s\,[\mathrm{km/sec}]). \tag{7}$$

## 3 THE CURRENT NEAREST STARS

Table I gives positional, kinematic and magnitude data for the five stars currently closest to the Sun, based on data drawn from the Gliese Catalogue (Jahreiss 1993, Morrison 1992). Data are also included for three other star systems, Gliese 65, Ross 248 and AC+79° 3888, for reasons which will become apparent.

TABLE I

*Current closest stars*

| Name | α (2000·0) δ | $d_0$ (pc) | $\mu$ (arcsec/yr) | $R_v$ (km/sec) | $M_v$ |
|---|---|---|---|---|---|
| (1) Proxima | $14^{\mathrm{hr}}\,30^{\mathrm{min}}\;-62°\,41'$ | 1·295 | 3·81 | −16* | 11·1v** |
| (2) α Cen A | $14^{\mathrm{hr}}\,40^{\mathrm{min}}\;-60°\,50'$ | 1·335 | 3·69 | −26† | 0·0 |
| (3) α Cen B | $14^{\mathrm{hr}}\,40^{\mathrm{min}}\;-60°\,50'$ | 1·335 | 3·69 | −18† | ·13 |
| (4) Barnard's | $17^{\mathrm{hr}}\,58^{\mathrm{min}}\;+04°\,34'$ | 1·835 | 1031 | −111 | 9·5 |
| (5) Wolf 359 | $10^{\mathrm{hr}}\,57^{\mathrm{min}}\;+07°\,01'$ | 2·392 | 4·70 | +13 | 13·5v |
| (Gleise 65A | $1^{\mathrm{hr}}\,39^{\mathrm{min}}\;-17°\,57'$ | 2·683 | 3·37 | +29†† | 12·5v) |
| (Gleise 65B | $1^{\mathrm{hr}}\,39^{\mathrm{min}}\;-17°\,57'$ | 2·683 | 3·37 | +32†† | 13·0v) |
| (Ross 248 | $23^{\mathrm{hr}}\,42^{\mathrm{min}}\;+44°\,10'$ | 3·165 | 1·62 | −78* | 12·3) |
| (AC+79° 388 | $11^{\mathrm{hr}}\,48^{\mathrm{min}}\;+78°\,41'$ | 5·208 | 0·86 | −112 | 10·8) |

*Notes*:
$M_v$ is present visual magnitude; * Gliese catalogue value, see section 4; † barycentric $R_v$ of A/B system is −22·7 km/sec; †† barycentric $R_v$ of A/B system is +31 km/sec; ** v = variable.

## 4 THE PRESENT, PAST AND FUTURE STATUS OF PROXIMA

Table I shows that Proxima is clearly the closest star to the Sun at present; the $1\sigma$ error on its Gliese catalogue parallax is 0·004 arcsec, compared to 0·005 arcsec on that for α Cen A/B, which leads to a probability of less than 1 in 50000 of α Cen A/B being closer to the Sun.

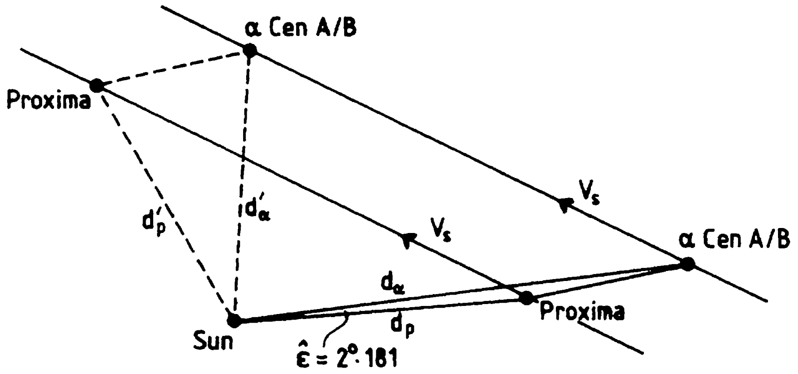

FIG. 1. The geometry and kinematics of α Cen A/B and Proxima.

When did Proxima acquire its current status as closest star to the Sun, and when will it lose it? The answer to these questions depends, of course, on the motion of Proxima itself. Surprisingly, almost 80 years after its discovery, the kinematics of Proxima are still a cause of controversy.

Most authorities (see, e.g. van de Kamp 1971) state that Proxima is in a bound orbit about α Cen A/B; indeed, the star is often referred to as α Cen C. However, detailed analysis of the relative motion of α Cen A/B and Proxima show that the currently most widely-quoted value of the radial velocity for Proxima, $-15{\cdot}7 \pm 3{\cdot}3$ km/sec (Thackeray 1967), is inconsistent with the bound orbit hypothesis (Matthews & Gilmore 1993). Such a radial velocity leads to a velocity for Proxima relative to α Cen A/B five times greater than the escape velocity of the binary at Proxima's current separation, and thus suggests that Proxima is simply passing through the α Cen A/B system.

However, more precise unpublished measurements of Proxima's radial velocity, made during ESO's Coravel programme, are consistent with the bound orbit hypothesis, a conclusion which is also supported by probabilistic arguments (Matthews & Gilmore 1993). In analysing Proxima's motion, we henceforth assume that this star is indeed in orbit about α Cen A/B.

Current data reveal little detail about Proxima's orbital motion. The parallaxes and angular separation of Proxima and α Cen A/B on the sky ($2°{\cdot}181$) imply that the semimajor axis of Proxima's orbit is at least 13000 AU. With a total system mass of $2{\cdot}13\ M_\odot$ (Kamper & Wesselink 1978), this implies an orbital period of $\geqslant 10^6$ yr. The data in Table I imply that the α Cen A/B/Proxima system makes its close approach on a timescale 35 times shorter than this. We may thus neglect the effect of Proxima's orbital motion to a first approximation, and assume that Proxima is bound to α Cen A/B, and simply shares that system's space motion (see Fig. 1).

This approximation makes the calculation of Proxima's space trajectory considerably simpler. However, the large angular separation of Proxima from α Cen prevents us from calculating this trajectory using the proper motion and radial velocity of Proxima's primary, α Cen A/B, alone. Instead, we must convert these kinematic data into the values they imply for Proxima if the latter has the same total space motion, taking into account the spatial separation between Proxima and α Cen A/B.

To do this, we follow the coordinate transformation approach of Kamper & Wesselink. Taking $R_v = -22{\cdot}7$ km/sec for the barycentre of α Cen A/B, we then find that for Proxima to share the space motion of its primary, we require that its radial velocity be $R_v(\text{bound}) = -22{\cdot}37$ km/sec and its tangential velocity be $v_t(\text{bound}) = 23{\cdot}66$ km/sec. Using these values, we may now calculate the space trajectory of Proxima using Eqn (3), and answer a number of questions about the past and future status of Proxima.

### 4.1 *The beginning of Proxima's reign*

Only stars now showing red-shifted radial velocities could have been closer to the Sun than Proxima in the past.

Using the data for $R_v > 0$ stars from the Gliese catalogue together with the velocity components for Proxima calculated above we find that the binary system Gliese 65 A/B (L 726-8/UV Cet) was the last stellar object to have come closer to the Sun than Proxima. Central values for the respective kinematic parameters show that this faint binary lost its status to Proxima about 32000 yrs ago; uncertainties in the parallaxes, proper motions and radial velocities for the two stellar systems give this figure an error of about ±2000 yrs.

### 4.2 *The close approach of Proxima*

Using Proxima's velocity components in Eqns (5) and (6), we obtain a closest approach distance for Proxima of $d_c = 0{\cdot}941$ pc, and a time of closest approach of 26700 yrs from now.

On the basis of data quoted in the Gliese catalogue, this implies that Proxima has the closest approach distance of any known star. However, the Gliese-based close approach distance for Ross 248 is virtually identical, at $d_c = 0{\cdot}943$. Uncertainties in the kinematic parameters for Proxima and Ross 248 lead to $1\sigma$ errors in the close approach distances of these two stars of about 0·03 pc, i.e. over an order of magnitude larger than the difference between the central values. Thus, although central values of the various parameters in the Gliese catalogue suggest that Proxima makes the closest approach of any known star, little confidence can be placed in this conclusion. Indeed, a more precise radial velocity for Ross 248 than that quoted in Gliese, obtained recently by the Coravel programme ($R_v = -79{\cdot}2 \pm 0{\cdot}9$ km/sec, Duquennoy & Mayor 1993), leads to a close approach distance of $d_c = 0{\cdot}927$ pc for Ross 248, suggesting that this star will, in fact, make the closest approach of any known star. In short, current kinematic data are still too imprecise to identify the real title-holder of closest approaching star with any confidence.

### 4.3 *The end of Proxima's reign*

Using Eqn (3) with the bound hypothesis values for Proxima derived earlier and the Coravel radial velocity of Ross 248, one finds that Ross 248 comes inside the trajectory of Proxima 33000 years from now. This date, which has an associated uncertainty of about ±2300 yrs, will mark the end of

TABLE II

*Stars coming within Proxima's present distance*

| Name | $d_c$ (pc) | $t_c$ (yr) | $v_s$ (km/sec) | $M_c$ |
|---|---|---|---|---|
| (1) Ross 248† | 0·927 | 36000 | 83 | 9·6 |
| (2) Proxima†† | 0·941 | 27000 | 33 | 10·4 |
| (3) α Cen A* | 0·957 | 28000 | 33 | −0·7 |
| (4) α Cen B* | 0·957 | 28000 | 33 | 0·6 |
| (5) AC+79° 3888 | 0·971 | 44000 | 114 | 7·2 |
| (6) Barnard's | 1·153 | 10000 | 143 | 8·5 |

*Notes*:
$M_c$ is visual magnitude at closest approach, calculated from $M_c = M_v + 5\log_{10}(d_c/d_0)$; † based on Coravel data – see section 4; †† assumes bound orbit – see section 4; and * quoted $v_s$ is space velocity of barycentre.

Proxima's 65000-year reign as the closest star to the Sun; thus, like its predecessor Gliese 65 A/B, Proxima will lose out to a dwarf star.

## 5 THE FUTURE CLOSE APPROACH OF STARS

The frequency $F_e(r)$ with which stars come within a distance $r$ of the Sun can be estimated by assuming that the Sun travels with velocity $V_s$ through the Solar Neighbourhood, assumed populated by randomly-moving stars of number density $\rho_s$. We then have

$$F_e(r) = \sqrt{2}\pi r^2 \rho_s V_s. \tag{8}$$

The solar motion velocity $V_s$ is 19·5 km/sec, and $\rho_s$ is approximately $58/[(4/3)\pi \times 5^3] \sim 0{\cdot}11$ stars/pc$^3$. From Eqn (8) we then find a stellar encounter frequency of

$$F_e(r) \sim 10^{-5}\, r\,[\mathrm{pc}]^2\ \mathrm{yr}^{-1}. \tag{9}$$

Setting $r \leqslant 1{\cdot}295$ pc (Proxima's current distance), Eqn (9) implies that we would expect no more than about one star per 60000 years to come within Proxima's current distance from the Sun. How does this compare with the actual number, as predicted using current kinematic data for Solar Neighbourhood stars?

Candidate stars were identified by rearranging Eqn (5) to give the criterion

$$d_0 < 1{\cdot}295\{1 + (R_v/v_t)^2\}^{1/2}\ \mathrm{pc}. \tag{10}$$

We then found that six known stars have kinematic parameters implying that they will pass closer to the Sun than the current distance of Proxima. The closest approach distances, together with the time of this approach (all in the future), are shown in Table II.

The results in Table II show that we are approaching a time peculiarly rich in stellar encounters: over the next 50000 years, the rate of close stellar encounters is an order of magnitude higher than that predicted using Eqn (9).

As Figure 2 shows, although Ross 248 is the first to usurp Proxima's current status, it recedes from the Sun relatively rapidly, so that 42000 yrs from now it will again be further from the Sun than Proxima. By this time,

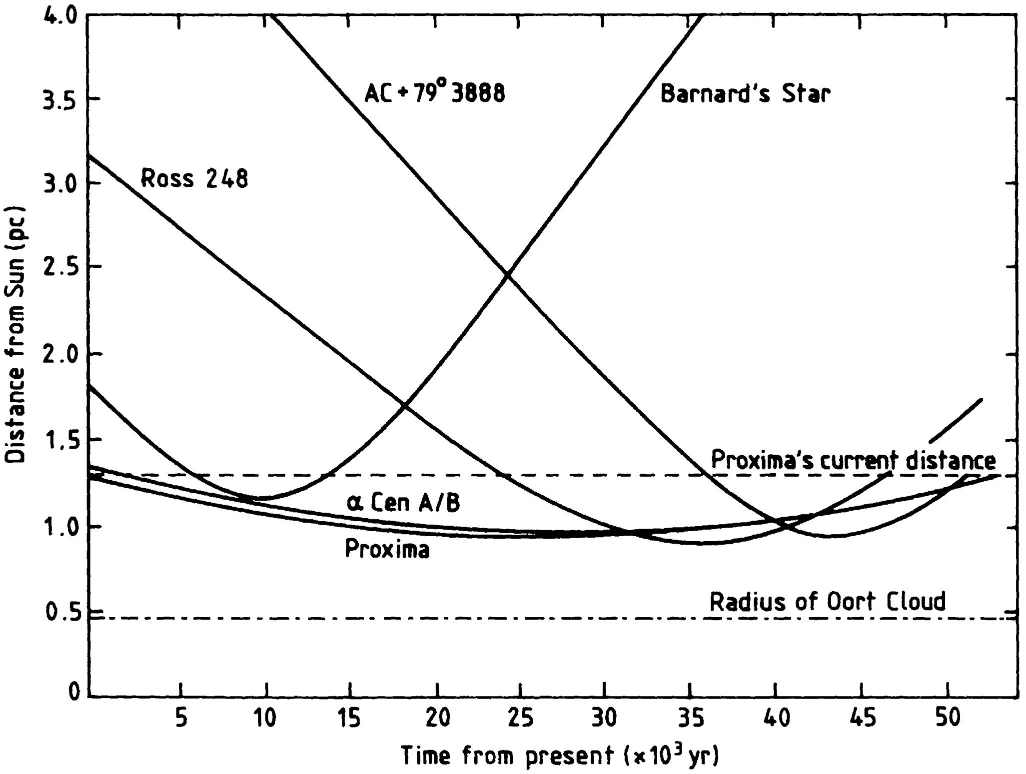

FIG. 2. The close approach of the six closest stars over the next 50000 yrs; note the cluster of encounters beginning about 33000 yrs from now. Proxima's trajectory assumes a bound state about α Cen A/B; that of Ross 248 assumes the Coravel value for radial velocity of −79·2 km/sec.

however, Proxima will have permanently lost its current status to the α Cen A/B system. This is a relatively massive stellar system, and it is to the dynamical effects of its close approach that we now turn.

## 6 PERTURBATIONS CAUSED BY α CEN A/B

All the stars listed in Table II, with the exception of the α Cen A/B binary system, are low-mass dwarfs whose close approach will have no appreciable effect on the Solar System. However, the relatively high total mass of the α Cen A/B system, combined with its close approach, raises the possibility that it may have some significant perturbative effect on the Solar System.

A star of mass $M_*$ passing within $d(t)$ pc of the Sun, mass $M_\odot$, will significantly perturb the (circular) orbits of planets about the Sun if the semimajor axes of those orbits exceeds a critical value $a_c$, where, by the inverse-square law

$$M_\odot/a_c^2 \leqslant M_*/(d(t)-a_c)^2. \tag{11}$$

Writing $R \equiv M_*/M_\odot$, we then obtain

$$a_c \geqslant d(t)\times(\sqrt{R}-1)/(R-1). \tag{12}$$

For α Cen A/B+Proxima we have a total mass of 2·13 $M_\odot$; inserting this into (12) then shows that α Cen A/B can only significantly perturb Solar

System orbits with semimajor axes exceeding 0·41 times the distance of this binary from the Sun. Thus $a_c \sim 80000$ AU at α Cen A/B's closest approach distance of $d_c = 0{\cdot}957$ pc.

As $a_c$ is three orders of magnitude greater than the size of the Solar System, we can conclude that no known star is capable of affecting the orbits of the planets. However, current estimates (Weissman, 1990) put the radius of the outer Oort Cloud, $R_0$, at about $10^5$ AU. This raises the possibility of a significant number of comets being perturbed by the close passage of α Cen A/B.

To estimate the total number of such comets, we note first that as α Cen A/B passes by the Oort Cloud, it imparts a velocity impulse to both the comets and the Sun.

This impulse has the potential to inject comets into the 'hole' in the velocity distribution of the Cloud's contents caused by captures by the Solar System; it is from this sub-population that potential earth-crossers will be derived.

The 'hole' is characterized by those comets with perihelion distances less than approximately $q_c \sim 15$ AU, which planetary perturbations remove from the Cloud (Bailey & Stagg 1990). Comets in the Oort Cloud spend most of their time near aphelion, and so those capable of filling the 'hole' will be those receiving a net velocity impulse relative to the Sun of the same order as the aphelion velocity corresponding to $q_c$ of 15 AU or less. The size of this net impulse is

$$\Delta V = 2GM_\alpha(1/d_c - 1/l_c)/V_\alpha \tag{13}$$

where $d_c$ is the comet-α Cen A/B distance, and $l_c$ is the Sun-α Cen A/B distance, and $V_\alpha$ and $M_\alpha$ are the space velocity and mass of the α Cen A/B system respectively. The aphelion velocity of a comet with semimajor axis $a$ and perihelion distance $q_c$ ($q_c \ll a$) is

$$V = \{GM_\odot\, q_c/(2a^2)\}^{1/2}. \tag{14}$$

Thus, to find the minimum semimajor axis of comet orbit capable of being perturbed into an Earth-crossing orbit, we equate (13) and (14), giving

$$a_c(1/d_c - 1/l_c) = \{(M_\odot/M_\alpha^2)\, q_c\, V_\alpha^2/8G\}^{1/2}. \tag{15}$$

To a good approximation, we can replace $a_c$ with $r_c/2$, where $r_c$ is the minimum distance from the Sun for a comet capable of being inserted into the 'hole'. Then, as $l_c = r_c + d_c$, we have

$$r_c^2 = 2K(l_c - r_c)\, l_c \tag{16}$$

where $K$ is equal to the rhs of (15). Solving this quadratic using the numerical value of $K$ of 0·71, we find that

$$r_c = 0{\cdot}67 l_c = 132000 \text{ AU}. \tag{17}$$

We can now estimate the number of comets in the Cloud which meet this criterion. Current models of the Cloud (Bailey & Stagg 1990) indicate that the number density of comets declines with distance from the Sun, $r$, according to $r^{\gamma-4}$, where $-1 \leqslant \gamma \leqslant 0$. To estimate the number of Earth-crossing orbits produced by α Cen A/B we must thus calculate the number

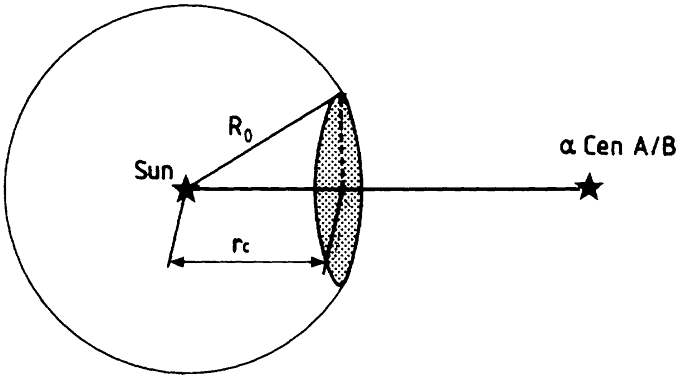

FIG. 3. The volume of the Oort Cloud perturbed by the close approach of α Cen A/B.

of comets in the volume of the Oort Cloud affected by the close encounter, and then find the proportion of those which will have $q_c \leqslant 1$ AU. We can approximate the volume affected by the velocity impulse by the spherical cap enclosed between $r_c$ given in Eqn (17) and the outer Oort Cloud radius $R_0$; see Fig. 3.

The number of Earth-crossing comets created by α Cen A/B is then of order $N$, where

$$N = \pi \int_{r_c}^{R_0} f(q_c)\, n(r)\, [R_0^{\,2} - r^2]\, dr \tag{18}$$

$$= \pi n_0 \int_{r_c}^{R_0} f(q_c)\, r^{\gamma-4}\, [R_0^{\,2} - r^2]\, dr \tag{19}$$

where $n_0$ is a normalization constant needed to ensure that the number density of the Cloud gives a total comet population of around $5{\cdot}10^{12}$; taking $\gamma = -0{\cdot}5$ leads to $n_0 \sim 6{\cdot}10^{17}$. The factor $f(q_c)$ is the fraction of comets perturbed by α Cen A/B with perihelia less than $q_c$ and is equal to $4/r$ in our case (Bailey & Stagg 1990).

Performing the integration between $R_0$, the outer Oort radius of $2{\cdot}10^5$ AU, and $r_c$, we find that about 200000 comets will be perturbed into Earth-crossing orbits by the close approach of α Cen A/B, making their approach in $\sim 2{\cdot}10^7$ yr.

## 7 CONCLUSIONS

In this paper, we have used current distance and kinematic data for the nearby stars to investigate a number of questions about the past, present and future state of the Solar Neighbourhood.

A surprising feature of the results is how finely balanced the answers to many of these questions are. For example, the identity of the star making the closest known approach to the Sun changes if the radial velocity of Ross 248 is altered by just 1·5 km/sec.

The questions surrounding the kinematics of Proxima are even more finely balanced. Quite apart from tidying up a number of points raised in this paper, more precise kinematic data for Proxima would also cast important light on the astrophysics of flare stars (Benedict *et al.* 1993, Matthews & Gilmore 1993) and the dynamics of stars passing through the Galaxy.

We began this paper by stating that the Solar Neighbourhood is the volume of space around the Sun whose contents are known with reasonable accuracy. It seems clear, however, that there are still some substantial gaps in our knowledge of this small part of the Galaxy.

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