

per cell whereas ATL-2 expresses about 8,000 molecules per cell. Our results unequivocally demonstrate that the Tac-2 sequence encodes the IL-2 receptor.

Discussion

The amino acid sequence of the IL-2 receptor does not have any significant homology with any known eukaryotic genes (or oncogenes). Cloning of the IL-2 receptor gene will, however, allow new insights into the physiological function and mechanism by which the IL-2 and its receptor system regulates T-cell proliferation. These include elucidation of the three-dimensional structures of the ligand and receptor which can be produced in large quantities in *E. coli* or mammalian cells, and the molecular mechanisms of signal transmission via surface receptor in the hormone and lymphokine systems, via mutants of the IL-2 receptor gene.

Cloning of the IL-2 receptor gene will also allow us to test several hypotheses proposed for the mechanism of leukaemogenesis of ATL triggered by ATL-1, which has no typical oncogene sequence³³. The excessive numbers of IL-2 receptor on ATL cells may be similar to aberrant expression of the EGF receptor on certain transformed cell lines such as A431

(ref. 34). The homology between the *erb-B* oncogene and the cytoplasmic domain of the EGF receptor²⁸ has strengthened the hypothesis²¹⁻²³ that an excessive amount of the IL-2 receptor might alter the normal growth control of T cells. This can be directly tested by transfection of human T-cell lines by the IL-2 receptor cDNA clone. We can also examine whether the IL-2 receptor gene in ATL cells has any mutations. A unique lymphokine secreted from ATL cells, ATL-derived factor (ADF), enhances the expression of the IL-2 receptor³⁰. ADF may be responsible for the continued expression of the IL-2 receptor in many ATL-1-positive T-cell lines. It is of interest to know whether ADF is able to induce transcription of the IL-2 receptor gene in human T cells.

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LETTERS TO NATURE

Terrestrial catastrophism— Nemesis or Galaxy?

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The ~30 Myr periodicity associated with the Sun's motion through the central plane has been linked to geomagnetic reversals^{1,2}, biological extinctions³ and crater ages⁴⁻⁶. This periodicity is consistent with galactic theories of terrestrial catastrophism^{1,5}. It has been suggested, however, that the periodicity is controlled by a hypothetical stellar companion of the Sun ('Nemesis') in a highly eccentric orbit of arbitrarily chosen period which periodically sweeps the Oort cloud^{7,8}. Although the idea appears superficially attractive, there has been little or no attempt to relate it to what is already known about the Oort cloud and the environment in which the Sun-Nemesis system would have to exist. Thus, the inferred phase of the Nemesis cycle is inconsistent with such

evidence as there may be for a recent disturbance (~5 Myr) of the Oort cloud, namely the apparent non-equilibrium distributions of perihelia¹ and $1/a$ (ref. 9) and the enhancement of the short-period comet population^{10,11} (compare ref. 12). It also discounts the generally high glacial, magnetic and orogenic activity on Earth within this period and the Sun's recent passage through Gould's belt^{10,13}. However, the most serious problem is reconciling the approximately constant time-averaged cratering rate for the last ~3,000 Myr (ref. 14) and the stability of the proposed system. The long-period comet system is dynamically unstable, over the lifetime of the Solar System, against the perturbing action of molecular clouds¹⁵⁻¹⁷. Since the proposed companion star has an aphelion distance $Q \approx 180,000$ AU (that is, $P \approx 30$ Myr) as against ~40,000-50,000 AU for long-period comets, one expects its orbit to be unstable *a fortiori*. On the impulse approximation the specific energy change ΔE of the companion resulting from a change Δv in its velocity v relative to the Sun is

$$\Delta E = \frac{1}{2}(v + \Delta v)^2 - \frac{1}{2}v^2$$

or

$$\Delta E = v \cdot \Delta v + \frac{1}{2}(\Delta v)^2 \quad (1)$$

Considering only the random component $v \cdot \Delta v$, Oort¹⁸ derived an expression for the specific energy fed into a body of separation Q from the Sun in $t \times 10^9$ yr, as a result of encounters with

Table 1 Energy injected by various perturbers

Perturber	Energy, Δv^2 [(cm s ⁻¹) ²]
GMCs with $M = 2 \times 10^5 M_\odot$, $\nu = 40 \text{ kpc}^{-3}$	3.8×10^9
Molecular clouds with $M = 2 \times 10^4 M_\odot$, $\nu = 400 \text{ kpc}^{-3}$	9.6×10^9
Stars	4.2×10^9
Σ	17.6×10^9
Energy required for escape	0.9×10^8

point masses. Modifying¹⁵ to allow for the effect of penetrating encounters with molecular clouds of mass M solar masses, radii R AU and number density $\nu \text{ kpc}^{-3}$, one finds

$$\Sigma \Delta v^2 = 740\nu \left(\frac{M}{2.21 \times 10^5 M_\odot} \right)^2 \times \left(\frac{Q}{R} \right)^2 \left(\frac{t}{4.5 \times 10^9 \text{ yr}} \right) 10^8 \quad (\text{cms}^{-1})^2 \quad (2)$$

The energy injected by various perturbers over 4.5×10^9 yr is listed in Table 1. According to Sanders¹⁹ recent determinations of the mass of the molecular cloud system agree to within a factor ~ 2 , whilst the column density of molecular clouds is $\sim 5 M_\odot \text{ pc}^{-2}$ at the solar distance, the mass-averaged mean mass of giant molecular clouds (GMCs) being $\sim 5 \times 10^5 M_\odot$. The first two entries in Table 1 each correspond to a column density $\approx 1 M_\odot \text{ pc}^{-2}$ and are therefore below the extreme lower limit of mass allowed by the data. There is also considerable substructure within GMCs, which adds substantially to the energy injected: thus GMCs ($\sim 10^5$ – $10^6 M_\odot$) appear to comprise aggregates of molecular clouds ($\sim 10^4 M_\odot$). We consider here three extreme models which are likely to encompass all reasonable possibilities: GMCs are uniform throughout their interiors (rows 1+3); GMCs do not exist, only molecular clouds (rows 2+3); GMCs comprise molecular clouds as substructure (rows 1+2+3). It seems that even with the most conservative assumption the energy injected into the Sun/Nemesis binary by molecular clouds and stars is at least an order of magnitude greater than its binding energy and that the system could not survive in its postulated state for 4.5×10^9 yr. Most probably, the sum of the injected energies is ~ 200 times that required to eject the companion star from the Solar System. The probable survival time can be found from equation (1) by equating the energy input to the binding energy whence it is found that, in the most likely case of rows 1+2+3, the formal survival time is ~ 50 Myr. Considering only the effect of uniform GMCs (rows 1+3), the survival time is found to be ~ 100 Myr. The rate of energy input is decreased by a factor ~ 1.5 – 2 allowing for the exponential z -distribution of molecular clouds¹⁶, and increased by factors ~ 2 and ≥ 2 allowing for gravitational focussing and a more gaseous past Galaxy respectively¹⁷.

The dissolution time τ of a binary system has been derived also by Chandrasekhar²⁰ neglecting the random component in (1) and considering only the systematic unbinding term $\frac{1}{2}(\Delta v)^2$. Adjusting his formula slightly to allow for the high eccentricity of Nemesis, one finds

$$\tau \approx \frac{7 \times 10^{13}}{\nu M Q^{3/2}} \times 10^9 \text{ yr} \quad (3)$$

yielding similar survival times, for example $\tau \sim 100$ Myr for uniform GMCs with $\nu = 40 \text{ kpc}^{-3}$ and $M = 2 \times 10^5 M_\odot$. Putting these two effects together (equation (1)), it is evidently unlikely that the Sun–Nemesis system will survive the Galactic environment for more than two or three revolutions.

In addition to the disruptive influence of encounters with molecular clouds and stars, the somewhat lesser effect of the Galaxy's smoothed-out mass distribution has to be considered. The disturbing potential due to the Galaxy is $\phi = -\frac{1}{2}(\alpha x^2 + \gamma z^2)$, with $\alpha \sim 1.6 \times 10^{-30} \text{ s}^{-2}$, $\gamma \sim -4.8 \times 10^{-30} \text{ s}^{-2}$, in a heliocentric

rotating coordinate system with x -axis directed towards the galactic anticentre, y -axis in the direction of rotation and z -axis towards the north galactic pole²¹. The critical Hill surface, beyond which orbits around the Sun are unstable, is roughly a tri-axial ellipsoid with $x_{\text{max}} \approx 300,000 \text{ AU}$, $y_{\text{max}} \approx 200,000 \text{ AU}$, $z_{\text{max}} \approx 150,000 \text{ AU}$. Thus with aphelion $\sim 180,000 \text{ AU}$, the orbit of Nemesis is barely if at all stable. Take the orbit to be roughly rectilinear, let χ represent the angle between orbit and x -axis, and consider the perturbing forces acting on the companion while its radius vector $r > a = 10^5 \text{ AU}$, which will hold for about half the orbital period. Over this time, the x -component of the galactic field satisfies $\ddot{x} = \partial\phi/\partial x \approx \alpha a \cos \chi$, whence $|\dot{x}| \approx (\alpha a \cos \chi) T/2$. With $a = 1.5 \times 10^{18} \text{ cm}$, $T = 9 \times 10^{14} \text{ s}$, $\cos \chi = 1$ one obtains $|\dot{x}| \approx 0.05 \text{ km s}^{-1}$. Likewise $|\dot{z}| \approx 0.15 \text{ km s}^{-1}$. These perturbations should be compared with the aphelion velocity of Nemesis, $\sim 0.03 \text{ km s}^{-1}$, and the circular velocity at $180,000 \text{ AU}$, $\sim 0.07 \text{ km s}^{-1}$. It is clear that the velocity vector of the companion star will be grossly perturbed around its aphelion: the binary system would not in general maintain the high eccentricity necessary for Oort cloud perturbations and indeed might not survive even a single revolution. Thus, the Galaxy's smoothed-out mass distribution is also an important factor, though if one were to (1) overlook molecular cloud perturbations; and (2) adopt a binary configuration with major axis close to the galactic plane, it is possible such a system might survive for $\geq 1 \times 10^9$ yr. Note also that the proposed binary characteristics are very rare or absent amongst observed systems. Thus among binaries with solar type primaries, only $\sim 1\%$ have periods in excess of 0.3 Myr, the computed periods amongst common proper motion pairs ranging from 3.5 to $820,000$ yr with mean $67,000$ yr and median $3,100$ yr. Furthermore, only $\sim 3\%$ of binaries have eccentricities ≥ 0.75 . These facts are of course consistent with disruption by molecular clouds and the Galaxy.

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Dynamical constraints on the mass and perihelion distance of Nemesis and the stability of its orbit

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It has been suggested^{1,2} that the observed periodic extinction of species at intervals of 26 Myr (ref. 3) may be catalysed by a hypothetical stellar companion of the Sun, Nemesis, with an orbital period of 26 Myr. The passage of a stellar companion through the inner comet cloud⁴ will fill the loss cone of these comets and cause a comet shower to enter the planetary system. It has been estimated that about 20 – 30 comets will hit the Earth during a shower, which

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lasts less than a million yr. Such Earth impacts would produce considerable environmental stress and may lead to widespread extinction of species⁴. I now investigate the effect of Nemesis on the comets in the inner comet cloud. This is used to determine the minimum required mass of Nemesis and its minimum required perihelion distance. The effect of passing stars on the stability of the orbit of Nemesis is investigated, and the probability of its having passed within the planetary system estimated.

My previous calculations⁴ were for a passing star in a hyperbolic orbit with an impact velocity of 30 km s^{-1} , which is very much greater than the orbital velocity of a long-period comet. This allowed an impulse approximation to be used. However, Nemesis has an orbit similar to that of the comets in the outer, steady-state or Oort comet cloud, so its orbital velocity is similar to that of the comets which it perturbs. A series of exact three-body calculations are used to determine the amount by which Nemesis perturbs the orbits of the comets in the inner cloud.

I consider comets having semimajor axes of 4,000 AU, which is about the maximum semimajor axis of the comets needed to produce a death shower. In the computer calculations, Nemesis is assumed to be a black dwarf with a mass of either $M_N = 0.05 M_\odot$, or $M_N = 0.005 M_\odot$. If the orbital period of Nemesis is 26 Myr and its mass is $0.05 M_\odot$, the semimajor axis of its orbit is $a_N = 89,200 \text{ AU}$ by Kepler's Third Law.

Because of the large semimajor axis of its orbit, Nemesis crosses the orbits of comets having semimajor axes of 4,000 AU at very nearly the parabolic speed. This means that the pericentre passage of Nemesis can be well approximated by modelling it as an object in a hyperbolic orbit with a velocity at infinity of 0.1 km s^{-1} , which is an order of magnitude less than its orbital velocity at pericentre passage. This approximation allowed me to use my massive, very accurate computer code which was originally applied to encounters between a binary system and a stellar intruder (refs 5, 6 and refs therein). The calculations used a representative comet orbit with a semimajor axis $a_c = 4,000 \text{ AU}$ and an eccentricity $e_0 = 0.999$ (see Table 1).

The loss cone comets are long-period comets which pass within the orbits of Jupiter and Saturn at perihelion. Such comets are lost by their ejection into hyperbolic orbits in a time comparable with the original orbital period of these long-period comets^{5,6}. They are not present unless perturbations by passing stars have deflected fresh comets into the loss cone within the previous orbital period. The latter situation occurs in the steady-state for comets in the classical Oort cloud⁴ (comets with semimajor axis, $a_c > 2 \times 10^4 \text{ AU}$). Comets with semimajor axis $< 2 \times 10^4 \text{ AU}$ only have their loss cones filled episodically by passing stars. An intense comet shower enters the planetary system whenever a close stellar passage occurs⁴.

To fill the loss cone of the comets in the inner cloud requires that the mean change in their pericentre distance $\langle \Delta q \rangle$ exceed the semimajor axis of the orbit of Saturn or $\langle \Delta q \rangle > 9.5 \text{ AU}$. Table 1 shows that for a Nemesis mass of $M_N = 0.05 M_\odot$ and for comets with semimajor axes $a_0 = 4,000 \text{ AU}$, this requires that the closest approach of Nemesis, its pericentre distance, be $< 2.6 a_0 = 1.04 \times 10^4 \text{ AU}$. Since the semimajor axis of Nemesis is $a_N = 89,200 \text{ AU}$, this requires that its orbital eccentricity be at least $e_N \geq (1 - R_{\min}/a_N) = 0.88$.

The orbit of Nemesis has been greatly perturbed by passing stars, so the probability of its having a given eccentricity is dictated by conditions of statistical equilibrium rather than by its initial eccentricity. The probability of its having an eccentricity e or greater at some arbitrary time is given by⁴

$$P_e = (1 - e^2) \quad (1)$$

For $e = 0.88$, we note that $P_e = 0.23$. Invoking the Ergodic Hypothesis that a time average for one object produces the same distribution as an ensemble average over many objects, we anticipate that ~23% of the time its orbital eccentricity is high enough for Nemesis to induce an intense comet shower at its pericentre passage. For a fixed value of Nemesis's pericentre distance q_N , the mean change in the pericentre distance of the comets with $a_c = 4,000 \text{ AU}$ scales as

Table 1 Relaxation of comet orbits by Nemesis

p/a_0	R_{\min}/a_0	$\Delta q/(\text{AU})$	N
$M_N = 0.05 M_\odot$			
2.5	0.134	84.8	100
5.0	0.531	134	551
9.0	1.68	149	551
10.0	2.06	79	551
11	2.47	12.8	551
12	2.91	4.1	100
15	4.41	1.7	100
20	7.41	0.7	100
$M_N = 0.005 M_\odot$			
5.0	0.554	2.3	551
9.0	1.75	7.4	551
10.0	2.14	1.3	551
11.0	2.57	0.54	551

$V = 0.1 \text{ km s}^{-1}$; $a_0 = 4 \times 10^3 \text{ AU}$; $e_0 = 0.999$. Impact parameter p , and closest approach $R_{\min} = q_N$ are shown in units of the semimajor axis of the comet orbit. $\langle \Delta q \rangle$ is the mean change in the pericentre distance of the comets.

Table 2 Maximum perihelion distance of Nemesis

M_N/M_\odot	$q_{\max}(a_0)$	$q_{\max}(\text{AU})$	e_{\min}	P_e	$1 - F_N$
0.015	1.7	6,800	0.92	0.15	0.12
0.02	2.1	8,400	0.91	0.17	0.13
0.05	2.6	10,400	0.88	0.21	0.16
0.10	4.0	16,000	0.85	0.27	0.20
0.20	7.4	30,000	0.66	0.60	0.40

e_{\min} is the minimum orbital eccentricity of Nemesis required by q_{\max} . P_e gives the fraction of the time during which its eccentricity exceeds e_{\min} .

$$|\Delta q_c| \propto \frac{M_N^2}{M_\odot + M_N} \quad (2)$$

in the impulse approximation. In this approximation, we expect that a Nemesis with $M_N = 0.005 M_\odot$ would produce a $|\Delta q_c|$ about 96 times smaller than a Nemesis with $M_N = 0.05 M_\odot$. The scatter in the exact numerical results of Table 1 are fairly large, but they indicate that the lower-mass Nemesis produces a $|\Delta q_N|$ about twice that predicted by scaling from $M_N = 0.05 M_\odot$ using the impulse approximation.

Applying the scaling law given by equation (2) to the data in Table 1, we can find $|\Delta q_c|$ for other possible masses of Nemesis. Table 2 shows, as a function of M_N , the maximum value of q_N that would still allow the perturbations by Nemesis to fill the loss cones at pericentre passage (that is, still result in $|\Delta q| \geq 9.5 \text{ AU}$).

If we correct for the small breakdown in the scaling law indicated by the computer calculations for $M_N = 0.005 M_\odot$, we see that a Nemesis with a mass $M_N = 0.01 M_\odot = 10 \text{ Jupiter masses}$ may be close to the minimum required mass, but a Nemesis with $M_N = 0.005 M_\odot$ is well below the minimum mass.

When the loss cone is filled, the fraction of the comets of semimajor axis a_c which have pericentre distances of q_c or less is $F_1 = 2q_c/a_c$, for $q_c \ll a_c$ (ref. 4). Here F_1 is also the fraction of the comets of semimajor axis a_c which are lost per orbital period due to the perturbations by Jupiter and Saturn if $q_c \leq 9.5 \text{ AU}$. The fraction of the comets of a given semimajor axis surviving N loss cone fillings is given by

$$F_N = [1 - (2q/a_c)]^N \quad (3)$$

If the loss cone of the inner cloud comets were filled at every perihelion passage of Nemesis for the past $4.6 \times 10^9 \text{ yr}$ then $N = N_0 = 177$ assuming the orbital period of Nemesis has remained constant at $2.6 \times 10^7 \text{ yr}$. For comets with $a_c = 4,000 \text{ AU}$ and $q_c \leq 9.5 \text{ AU}$, $F_N = 0.43$ for $N = 177$. In this case, more than half these comets would be lost. However, the orbit of Nemesis is severely perturbed by passing stars. The factor P_e in Table 2 is the fraction of the time that its orbit is eccentric enough and

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The present results have been derived from an extensive series of numerical orbit calculations (including 10^7 stellar encounters) the details of which will be published elsewhere. These calculations take into account the perturbations of passing field stars as well as the galactic tidal field on the orbit of a double star; additional perturbations are caused by occasional passages close to molecular clouds and through spiral arms. The first two types of perturbations, stars and galactic tides, act continuously. The galactic tidal field has a nearly constant strength over the orbit of the Sun, and passing stars appear in large numbers: every million years the Sun encounters many different stars some of which actually pass through the orbit of the solar companion. Because of their intermittent character, the effects of molecular clouds and spiral arms are less important on a 250 Myr time scale on which the extinction record is well documented; these will be discussed in more detail elsewhere.

The strongest component of the tidal force acts perpendicular to the galactic plane, where the gradient of the galactic force field is steepest, and has a restoring character. The tidal force in the direction to the galactic centre is smaller by about a factor of six, and tends to pull a wide double star further apart. This radial force is composed of two parts, one of which stems from the radial gradient in the galactic force field and the other from the centrifugal force in the coordinate system rotating with the Sun in its path around the Galaxy. Another important effect in the rotating frame of reference is the Coriolis force acting in the galactic plane perpendicular to the motion of the companion. I have modelled all these effects in a linearized approximation, which is sufficiently accurate⁹.

Each field star passing close to the double star exerts a perturbing force which acts over a time interval much shorter than the orbital period of the binary, by a factor typically of the order a few hundred. Therefore, I have used the impulsive approximation, where the perturbing force is taken to act instantaneously at one point in the binary orbit. This approximation saves a factor of nearly 100 in computer time, and gives 1 Myr worth of orbit integration, featuring about 100 stellar encounters, every few seconds (rather than minutes¹⁰) of central processing unit time on a VAX 11/780 computer.

To understand the relative importance of both types of perturbations, I consider first the galactic tidal field only, neglecting passing stars, and orient the major and minor axes of the orbit along two of the three principal axes of the tidal field. For each of these six choices, I have computed many orbits, all starting with the same eccentricity $e = 0.7$, but with different values for a , the length of the semi-major axis, to find an orbit with a periodicity of 26 to ~ 28 Myr (Kepler's third law is a poor approximation in the presence of strong tidal forces). The numerical values for the components of the tidal force have been computed from recent estimates at Oort's A and B constants ($A = 16$ and $B = -11$, in $\text{km s}^{-1} \text{kpc}^{-1}$, refs 11, 12) together with the inferred mass density in the solar neighbourhood which includes the unobserved galactic disk material³, while the Coriolis forces follow from the inferred galactic rotation frequency^{11,12}.

Figure 1a shows the largest tidal perturbations which occur for orbits with their major axis perpendicular to the galactic plane and minor axis perpendicular to the direction of the galactic centre (so that the galactic tidal force is purely restoring, which shortens the orbital period and therefore requires a larger, less stable orbit to satisfy a given orbital period). Figure 1b shows the most regular orbit, which lies in the galactic plane with its major axis pointing to the galactic centre.

Orbits parallel to the galactic plane are not affected by the strongest component of the tides, and thus are more regular and have a smaller amplitude than orbits which feel the compressive but overstabilizing tidal field component perpendicular to the galactic disk. Both effects suggest that a search for the companion star might have a higher chance of success at lower galactic latitudes (even though crowding is worse there), because (1) the fossil record as well as crater ages are more compatible with the regularity of Fig. 1b than with Fig. 1a, and (2) the

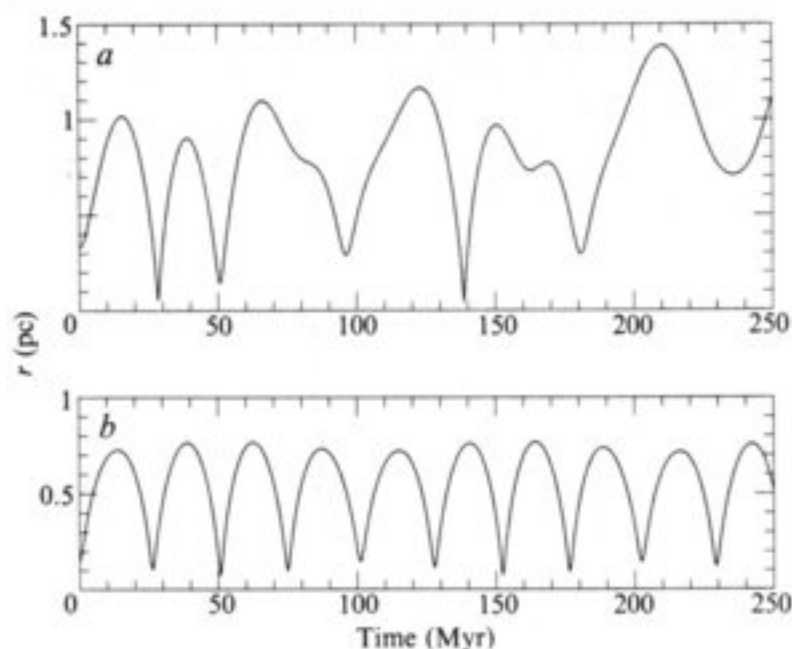


Fig. 1 The separation between the Sun and companion star under the perturbing influence of the galactic tidal field, in parsecs ($1 \text{ pc} \approx 206,000 \text{ AU}$). a, For an orbit perpendicular to the galactic plane; b, for an orbit in the plane.

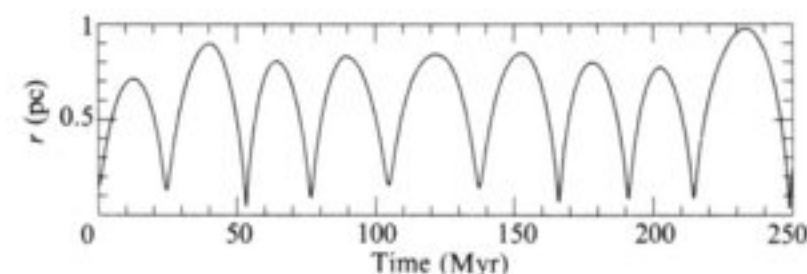


Fig. 2 The separation between Sun and companion star under the combined perturbing influences of passing stars as well as the galactic tidal field, for an orbit with the same initial conditions as in Fig. 1b.

smaller excursions in Fig. 1b make the orbit less vulnerable to perturbations by passing stars, which I now discuss.

I have immersed a double star in a field of passing stars, most of which cause only a tiny perturbation even when they cross the binary's orbit, because the total momentum transfer is proportional to the time spent in the encounter (typically only 0.1–1% of the orbital period). For the distribution of field stars I have accurately modelled the solar environment, using 10 discrete mass classes in the range 0.25 – $20 M_{\odot}$, each with their particular observed number density and velocity dispersion^{11,12}, with a total mass density of $0.06 M_{\odot} \text{pc}^{-3}$ ($0.02 M_{\odot} \text{pc}^{-3}$ of which resides in light stars of $0.25 M_{\odot}$, to model the unseen disk material; a choice of $0.05 M_{\odot} \text{pc}^{-3}$ in the form of $0.1 M_{\odot}$ stars would have given a similar cumulative effect). The procedure for generating the properly weighted random distributions of orbital elements has been described previously¹⁰ using a Monte Carlo approach to obtain scattering cross-sections in the gravitational three-body problem.

Figure 2 shows an orbit which starts out with exactly the same initial conditions as in Fig. 1b, but which is now subject to stellar perturbations as well as to the galactic tidal field. Note the fluctuations in the time intervals between successive close approaches (perihelion passages) of the companion, spanning a range 23 to ~ 34 Myr. This suggests that even completely accurate dating of mass extinctions and crater impacts should not be expected to yield perfectly sharp peaks in the power spectrum of a Fourier analysis. A more sensitive test of the hypothesis of an unseen solar companion follows rather from the prediction of a tight correlation between individual periods of enhanced cratering rates and periods of mass extinction (several authors have argued that an alternative explanation can be given using the Sun's periodic motion perpendicular to the

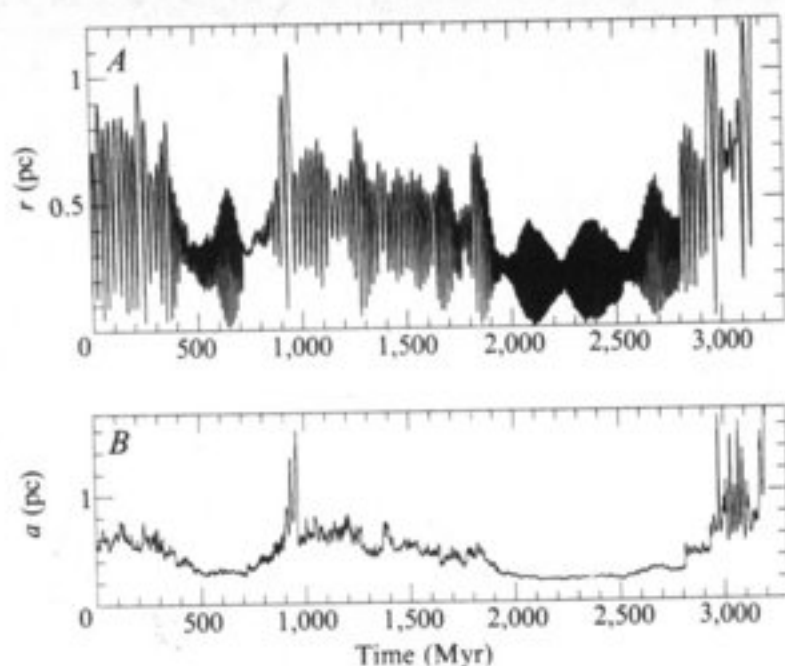


Fig. 3 A, The same orbit as in Fig. 2, followed until final dissolution around AD 3,200,000,000. B, The evolution of the semi-major axis of the orbit in a . The noise in the perturbations has a fine structure down to 0.01 Myr.

galactic plane^{8,14}; however, it is hard to understand why both extinctions and cratering seem to occur when the Sun is furthest away from the galactic plane^{1,7}). Although the intermediate time intervals cannot be predicted individually, their probability distribution can be obtained from orbit calculations, which thereby provide additional constraints.

Also note in Fig. 2 the significant scatter in the distance of closest approach. The number of comets directed into the inner planetary system at these times is strongly dependent on this distance, although for small perihelion distances a saturation effect might occur if the loss cone is filled completely^{3,4}. This could naturally explain why some mass extinctions have been so much more dramatic than others^{1,2}. The term 'loss cone' is used in analogy with plasma physics, where a mirror machine has a cone-shaped region in velocity space from which the plasma can escape. For the gravitational application the region in velocity space from which comets are lost is really bounded by a loss hyperboloid-of-one-sheet¹⁵; this is sufficiently less euphonious that the term loss cone is preferable as long as it is understood to refer to a strictly hyperboloid geometry.

I have computed several hundred orbits, each starting with a revolution period 26 to ~28 Myr, and with an initial distribution isotropic in space. As mentioned above, the orbits parallel to the galactic plane live longer than those perpendicular to the plane. About half of the total sample of orbits dissolved within 1,000 Myr, in agreement with analytical estimates¹⁶⁻¹⁸. A more quantitative discussion has to include the complicated dependence of the dissolution rate on the orientation of the orbit with respect to the Galaxy, and lies beyond the scope of the present letter. These half lives decrease if the effects of molecular clouds and spiral arms are taken into account, but the decrease is sensitively dependent on the distribution of molecular clouds, which is observationally less well determined than that of the field stars. A realistic guess for the final life time would be a value larger than 500 Myr, because (1) the Sun is, at present, ~1 kpc closer to the galactic centre than on average, and (2) the Sun has an unusually low velocity perpendicular to the galactic plane at present (Wielen, personal communication). Both effects strongly diminish the influence of giant molecular clouds which are concentrated towards the galactic plane and towards the galactic centre, in contrast with results by other authors¹⁸⁻²⁰. A detailed analysis of orbit calculations which include these effects will be published elsewhere.

With a half life of 1,000 Myr, survival times of a few 1,000 Myr still occur frequently. Figure 2 shows a double star orbit which lasts for 3,200 Myr, as plotted in Fig. 3A, to illustrate the richness of the spectrum of perturbations. The final breakup of the double star occurs after a random walk in orbital parameter space,

through the combined influence of more than 100,000 individual encounters with field stars. These perturbations can be seen more clearly in Fig. 3B, which plots the semi-major axis a of the orbit. Typically, every 10,000 yr another field star begins an encounter (included in the numerical calculations whenever it occurs within a distance of five times the semi-major axis) each of which lasts for a 100,000 yr. Occasionally a large jump occurs, which can be caused in any of three different ways; the passing star can be extra massive, come extra close or move extra slowly, in each way increasing the total momentum transfer.

The noise in Fig. 3B is strongly dependent on the size of the orbit. For $a < 0.3$, on the right-hand side of Fig. 3B, the jitter has died down by nearly an order of magnitude. This is because fewer stars pass close to a tighter orbit, and larger perturbations are required significantly to affect a tighter and therefore more energetic orbit. During these lulls in stellar perturbations, the galactic tidal field makes itself visible in the slow modulation of the eccentricity with a period of about 300 Myr, as can be seen in the rising and falling of the amplitude of the excursions in r on the right-hand side of Fig. 3A.

The closest encounter in Fig. 3A brings the companion to a distance of 800 AU from the Sun, by AD 2,100,000,000. Encounters much closer than that are rare during the lifetime of the Solar System, as I have found from orbit calculations starting at an initial separation of 0.1 pc (resulting in a half life of ~5,000 Myr). This suggests that a planetary system can indeed survive the presence of a distant solar companion, as the expected induced eccentricity for the orbits of the outer planets is < 0.01 (ref. 21), even if the companion would come in as close as 200 AU. A detailed study of the perturbations on the planets would nevertheless, be very interesting; it would probably not put very stringent restrictions on the hypothesis of a solar companion, but it might explain the ill-understood irregularities in the planetary system.

Figures 2 and 3 chart only one of the many possible future evolutions of the orbit of a solar companion. Each individual orbit calculation yields vastly different results, since the passing stars exert a stochastic perturbing force on the double star. These perturbations are unpredictable on a short time scale and difficult to treat analytically, even using the average for longer time scales, because of the complicated interference with the galactic tidal field. Each of the different future evolutions which I have calculated as starting with the initial conditions of Fig. 1b are equally likely to occur, as are many others starting from different initial conditions (but with the same initial orbital period of 26 to ~28 Myr).

The evolution of the hypothetical solar companion can be summarized as follows: the original orbital period at the time of the formation of the Solar System was probably in the range 1 to ~5 Myr, much shorter than the present value of 26 to ~28 Myr; and the final escape of our companion star might take place relatively soon, on a time scale of the order of 1,000 Myr.

After completing this work I received a preprint by Smoluchowski and Torbett²², whose calculations of tidal disturbances of comets agree with the present paper.

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Orbital stability of solar companions linked to mass extinctions

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Recent suggestions of a solar companion

extinction events and periodicities in the Earth's climate. First, it has been proposed that the Solar System through the impact of 30 Myr molecular clouds, or sub-cloud comets, suggested^{6,7} that a tentative name for that perihelion Oort cloud⁸. scattering of such impact the Earth causing climate best estimates of major axes in such orbits are not known. numerical models of inclination with respect to the galactic plane for the required molecular clouds.

Calculations of fourth-order resonances are framed as a problem from the Sun. Tidal perturbations well as Coriolis forces posed on the tidal field of the Sun and given per

where z is in the vertical direction, 'gravitational' perturbations from the galactic centre (~30 Myr) is resonant and significant, even if the companion is not known.

The calculations of a solar companion