Search for Close Stellar Encounters with the Solar System from Data on Nearby Dwarfs

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Abstract—Trigonometric parallaxes measured with ground-based telescopes of the RECONS consortium as part of the CTIOPI program are used to search for stars that have either had an encounter with the solar system in the past or will have such an encounter in the future, at distances of less than a few parsecs. These are mainly low-mass dwarfs and subdwarfs of types M, L, and T currently at distances of less than 30 pc from the Sun. Six stars for which encounters with the solar orbit at distances of less than 1 pc are possible have been identified for the first time. For example, the minimum distance for the star **SOZ 3A will $0.72 \pm 0.11$ pc at an epoch of $103 \pm 44$ thousand years in the future.

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1 INTRODUCTION

The Sun is surrounded by the cometary Oort cloud. It is believed that its radius is approximately $1 \times 105$ AU (0.5 pc). At such distances, the gravitational bonds between these comets and the Sun are weak, and their orbits can be subject to slight perturbations due to various external factors. These factors include the random passage of a field star, the influence of giant molecular clouds, and the influence of the overall Galactic gravitational field [1–3].

Passages of Galactic field stars near the Oort cloud or even penetration into this cloud can induce the formation of cometary showers moving in the vicinity of the giant planets [4]. The possible bombardment of the Moon and Earth with such cometary bodies is not ruled out [5].

Numerous studies have been dedicated to searches for close encounters of stars with the solar orbit. About 200 HIPPARCOS stars [6] that either underwent a close encounter with the solar system at a distance of less than 5 pc in the past or will do so in the future, at epochs from $-10$ to $+10$ million years, are currently known. According to the estimates of Garcia–Sánchez et al. [7], the frequency of stellar encounters at distances of less than 1 pc is roughly 12 stellar encounters per one million years.

Several specific stars have a high probability of penetrating into the vicinity of the Oort cloud. As was first shown by Garcia–Sánchez et al. [8], and later confirmed by other data [7, 9, 10], the star GJ 710 (a K7V dwarf) may have a very close encounter with the solar orbit. For example, Bobylev [9] used data from the revised HIPPARCOS catalog to determine this star’s minimum distance to be $d_m = 0.31 \pm 0.17$ pc at the epoch $t_m = 1447 \pm 60$ thousand years in the future. Finally, a completely new estimate was made by Berski and Dybczyński...
using parallaxes and proper motions measured by GAIA [12], yielding $d_m = 0.065 \pm 0.030$ pc and $t_m = 1350 \pm 50$ thousand years. Thus, the star GJ 710 currently holds the record for the closest encounter.

The estimates $d_m = 0.25^{+0.11}_{-0.07}$ pc and $t_m = -70^{+0.15}_{-0.10}$ thousand years were obtained for the low mass binary system WISE J07203.20–084651.2 (M9.5+T5) in [13]. The total mass of this system is only about $0.15M_\odot$. Two more such stars are also known: HIP 85605 ($d_m \sim 0.1$ pc, $t_m \sim 330$ thousand years) [14] and HIP 63721 ($d_m \sim 0.2$ pc, $t_m \sim 150$ thousand years) [14, 15]. However, the trigonometric parallaxes for these last two stars are currently quite unreliable. Dybzhiński [9] carried out numerical simulations of the evolution of cometary orbits based on the example of the penetration of GJ 710, with a mass of about $0.6M_\odot$, into the Oort cloud. These simulations showed that Galactic tides can give rise to a greater flux of comets in the inner part of the solar system than a star with these parameters. The conclusion that a star such as GJ 710 has a small destructive influence on the Oort cloud was also drawn in [16]. However, the later simulations of [11] with new parameters for a closer flyby of this star showed the possibility of an appreciable flux corresponding to tens of comets per year over three to four million years.

The aim of our study was to search for stars that could undergo close encounters with the Sun, based on a sample of nearby stars whose trigonometric parallaxes were measured using ground-based telescopes. Radial-velocity measurements obtained in the RAVE project [17] have recently become available for a large number of weak stars.

2 DATA

We used results obtained in the framework of the international Research Consortium On Nearby Stars (RECONS, http://www.astro.gsu.edu/RECONS/index.htm). Observation aimed at deriving stellar trigonometric parallaxes and proper motions were carried out in the Chilean Andes starting in 1999 as part of the Cerro Tololo Interamerican Observatory Parallax Investigation (CTIOPI), using two telescopes with mirror diameters 0.9 and 1.5 m. The mean accuracy of the trigonometric parallaxes is 3 milliarcsecond (mas).

The stars GJ 3379 (G 99–049) and GJ 3323 (LHS 1723) were identified in [18] as close-encounter candidates, based on a list of 100 nearby stars of the RECONS program. The amount of data available for analyzes of this sort has now appreciably grown.

The latest results of trigonometric parallax measurements conducted in the CTIOPI program are presented in [19–26]. The total list of stars with measured parallaxes and proper motions compiled based on these publications contains more than 500 objects, primarily M, L, and T dwarfs.

The RAdial Velocity Experiment (RAVE) [17] is dedicated to massive determinations of radial velocities for weak stars. Observations in the southern hemisphere on the 1.2 m Schmidt telescope of the Anglo–Australian Observatory began in 2003. Since then, five editions of this catalog (DR1–DR5) have been published. The mean uncertainty in the radial velocities is about 3 km/s.

We took the radial velocities used in our current study mainly from the RAVE DR4 catalog [27], which is accessible via the SIMBAD electronic database. As a result, based on the 500 stars of the initial CTIOPI list, we created a working database containing the measured trigonometric parallax, proper motion components, and radial velocity for each of 175 stars.
We especially dedicated this separate study to a search for close encounters with the Sun by stars whose trigonometric parallaxes were determined using specific ground telescopes. The reliability of these parallaxes enables a confident analysis of only a small circumsolar volume with a radius of no more than 25–30 pc. This makes it possible to apply simpler analysis methods, such as linear or epicyclic fitting.

3 METHOD

3.1 Epicyclic Orbit

Based on the epicyclic approximation [28], we constructed orbits of the objects studied in coordinates rotating about the Galactic center:

\[
\begin{align*}
    x(t) &= x_0 + \frac{u_0}{\kappa} \sin(\kappa t) + \frac{v_0}{2B} (1 - \cos(\kappa t)), \\
    y(t) &= y_0 + \frac{2\Omega_0 u_0}{\kappa^2} (1 - \cos(\kappa t)) + 2A \left( x_0 + \frac{v_0}{2B} \right) t - \frac{\Omega_0 v_0}{B \kappa} \sin(\kappa t), \\
    z(t) &= z_0 \cos(\nu t) + \frac{w_0}{\nu} \sin(\nu t),
\end{align*}
\]

where \( t \) is the time in millions of years (using the relation 1 pc/million years = 0.978 km/s); \( A \) and \( B \) are the Oort constants; \( \kappa = \sqrt{-4\Omega_0 B} \) is the epicyclic frequency; \( \Omega_0 \) the angular speed of Galactic rotation of the Local Standard of Rest (LSR), \( \Omega_0 = A - B \); and \( \nu = \sqrt{4\pi G \rho_0} \) the frequency of vertical oscillations, where \( G \) is the gravitational constant and \( \rho_0 \) the stellar density in the solar neighborhood. Equation (1) is written for heliocentric coordinates, where \( x \) is directed away from the Sun toward the Galactic center, \( y \) points in the direction of Galactic rotation, and \( z \) points in the direction of the Galactic north pole. The space velocities of stars \((u, v, w)\) are directed along the axes \((x, y, z)\).

The parameters \((x_0, y_0, z_0)\) and \((u_0, v_0, w_0)\) in the system of equations (1) denote the initial positions and velocities of the stars. The velocities \((u, v, w)\) were corrected for the peculiar motion of the Sun relative to the LSR, using the components \((U, V, W)_\odot = (11.1, 12.2, 7.3)\) km/s [29]. We took the local density of matter to be \( \rho_0 = 0.1 \ M_\odot/\text{pc}^3 \), in accordance with the estimate of [30], which gives \( \nu = 74 \) km/s/kpc. We used the values of the Oort constants \( A = 15.5 \pm 0.3 \) km/s/kpc and \( B = -12.2 \pm 0.7 \) km/s/kpc, found from masers with measured trigonometric parallaxes, which corresponds to \( \Omega_0 = 27.7 \) km/s/kpc and \( \kappa = 41 \) km/s/kpc. The height of the Sun above the Galactic plane was taken to be \( z_0 = 16 \pm 2 \) pc [32]. We neglected the gravitational interaction between the stars and the Sun.

3.2 Statistical Modeling

In accordance with the Monte Carlo statistical modeling method, we computed a set of orbits for each star ascribing random errors to the input data. We computed the approach parameter for the orbits of the stars and Sun, \( d(t) = \sqrt{\Delta x^2(t) + \Delta y^2(t) + \Delta z^2(t)} \), for each star. The epoch of minimum approach is characterized by the two numbers \( d_m \) and \( t_m \). We assumed that the errors in the stellar parameters were normally distributed with standard deviation \( \sigma \).
In practice, this worked as follows. We found a set of model orbits based on Eqs. (1). Random uncertainties in the equatorial coordinates, proper motion components, parallax, and radial velocity were added for each star. We then computed the mean values of \( d_m \), \( t_m \), and their standard deviations.

**RESULTS AND DISCUSSION**

For each of the 175 stars in our list, we constructed its orbit relative to the solar orbit in the interval from \(-1\) million years to \(+1\) million years. It turned out that many stars with huge radial velocities fell into the sample, which are most likely due to erroneous measurements in the RAVE4 catalog. Therefore, we restricted our consideration to 12 stars with approach parameters \( d_m < 2.3 \) pc, whose characteristics are given in Table 1. The figure shows the approach trajectories of these stars with the solar orbit.

The columns of Table 1 give (1) an ordinal number for the star, (2) an identification number, (3) the equatorial coordinates \( \alpha \) and \( \delta \), (4) the components of the proper motion \( \mu_\alpha \cos \delta, \mu_\delta \) and their uncertainties, (5) the trigonometric parallax \( \pi \) and its uncertainty, (6) the radial velocity \( V_r \) and its uncertainty, and (7)–(8) estimates of the approach parameters \( d_m \) and \( t_m \).

Table 2 gives the input coordinates and velocities of the selected stars. Many stars from this list have very high space velocities (exceeding 600 km/s). This would seem to indicate that they should be classified as hypervelocity stars, capable of escaping the gravitation of the Galaxy. The escape velocity at the Sun’s distance from the Galactic center depends slightly on the model used for the gravitational potential, and is about 550 km/s (see, e.g., [33]). Due to the high speeds of these stars, their flybys past the solar system are brief.

It is interesting that the RAVE4 catalog also gives the signal-to-noise ratio (SNR) and flags \( c_1-c_{20} \), describing the morphology of the spectrum. According to these characteristics, all the stars in our list with radial velocities \(|V_r| > 300\) km/s (Table 1) have very low SNRs.
| No. | Star     | α₂₀₀₀ | δ₂₀₀₀ | μα cos δ, μδ, mas/yr | π, mas | V₁, km/s | dₘ, pc | tₘ, Gyr |
|-----|----------|--------|--------|----------------------|--------|----------|--------|--------|
| 1   | L 87-10  | 16.028958 | -65.374250 | -323.11 ± 0.71 | 85.40 | -867 | 0.27 | 14 |
| 2   | LHS 3583 | 311.654500 | -81.720472 | 540.65 ± 0.71 | 94.72 | 970 | 0.42 | -11 |
| 3   | GJ 4274  | 335.779042 | -17.606944 | 304.11 ± 0.19 | 137.58 | 308 | 0.62 | -23 |
| 4   | ** SOZ 3A | 214.204500 | 13.807306 | 91.27 ± 3.90 | 111.15 | -87 | 0.72 | 103 |
| 5   | LHS 1351 | 32.825417  | -63.228055 | -682.47 ± 1.16 | 71.53 | 953 | 0.74 | -15 |
| 6   | LEHPM 4771 | 337.539416 | 53.748750 | -62.20 ± 0.04 | 63.70 | 940 | 0.93 | -17 |
| 7   | LHS 500  | 313.904666 | 14.065277 | 1415.40 ± 0.47 | 82.79 | 912 | 1.12 | -13 |
| 8   | G 99-049 | 90.014666  | 2.706555  | -468.10 ± 0.20 | -38.02 ± 0.04 | 193.60 | 30.2 | 1.25 | -161 |
| 9   | GJ 1157  | 185.755958 | 46.619000 | -742.72 ± 0.45 | 62.42 | -778 | 1.28 | 20 |
| 10  | GJ 729   | 282.455708 | -23.836222 | 637.86 ± 0.38 | 339.59 | -10.5 | 1.95 | 157 |
| 11  | GJ 1061  | 53.998708  | -44.512583 | -192.58 ± 0.12 | 1.63 | ±0.1 | ±0.02 | ±4 |
| 12  | CN Leo   | 164.120250 | 7.014666  | -3808.09 ± 0.30 | 413.13 | 19.3 | 2.28 | -14 |
Table 2: Initial velocities and coordinates of selected stars

| No. | \( (U, V, W) \pm (e_U, e_V, e_W) \), km/s | \( (x, y, z) \pm (e_x, e_y, e_z) \), pc |
|-----|-----------------------------------------|----------------------------------|
| 1   | \((-256, 466, 685) \pm (5, 9, 13)\) | \((-3.72, -6.23, -9.19) \pm (0.07, 0.11, 0.16)\) |
| 2   | \((-519, -643, -509) \pm (4.5, 4)\) | \((5.99, -6.80, -5.42) \pm (0.15, 0.17, 0.14)\) |
| 3   | \((136, 92, -262) \pm (42, 36, 79)\) | \((3.20, 2.74, -5.92) \pm (0.01, 0.01, 0.02)\) |
| 4   | \((-36, 5, -79) \pm (13, 1, 30)\) | \((3.64, 0.21, 8.23) \pm (0.16, 0.01, 0.37)\) |
| 5   | \((236, -543, -748) \pm (3.7, 9)\) | \((2.77, -8.23, -10.96) \pm (0.06, 0.19, 0.25)\) |
| 6   | \((526, -267, -722) \pm (6, 3, 8)\) | \((8.75, -3.64, -12.51) \pm (0.15, 0.06, 0.22)\) |
| 7   | \((587, 402, -578) \pm (14, 10, 11)\) | \((8.35, 5.68, -6.72) \pm (0.13, 0.08, 0.10)\) |
| 8   | \((-26.2, -16.8, 0.7) \pm (0.5, 0.2, 0.1)\) | \((-4.62, -2.11, -0.91) \pm (0.04, 0.02, 0.01)\) |
| 9   | \((-393, 629, -246) \pm (21, 39, 13)\) | \((7.20, -13.62, 4.41) \pm (0.07, 0.11, 0.16)\) |
| 10  | \((-12.0, 1.0, -7.2) \pm (0.1, 0.0, 0.1)\) | \((2.84, 0.57, -0.53) \pm (0.01, 0.00, 0.00)\) |
| 11  | \((3, 0, 25) \pm (1, 3, 4)\) | \((-0.70, -2.13, -2.97) \pm (0.01, 0.01, 0.01)\) |
| 12  | \((-27.9, -47.6, -13.7) \pm (0.1, 0.1, 0.2)\) | \((-0.59, -1.21, 2.01) \pm (0.01, 0.00, 0.00)\) |

(less than five, while the SNRs for “good” spectra should be an order of magnitude higher), and the spectra of all of these stars have gaps in their continua \((c_{1,2,3}=c)\) or are peculiar \((c_{1,2,3}=p)\). On this basis, we concluded that the radial-velocity measurements of these stars were of poor quality.

The RAVE radial velocities for the stars considered were usually obtained from one “poor” spectrum. However, the RAVE catalogs also contain stars for which several spectra of various quality were taken at various epochs. For example, four radial velocity measurements are available for the star TYC 4888-146-1, derived using four good spectra \((c_{1,2,3}=n)\), normal spectrum). All four values are close to \(V_r = -15\) km/s. However, the value \(V_r = 1897\) km/s is also presented in the RAVE5 catalog [34], found from a spectrum with gaps in its continuum \((c_{1,2,3}=c)\). All this strengthens our impression that stars with very high radial velocities in the RAVE catalogs are likely to be problematic.

Moreover, radial velocities obtained from spectra other than those from the RAVE program are available for the stars GJ 4274 and GJ 1157. For GJ 4274, \(V_r = -2.1 \pm 1.1\) km/s [35], implying \(d_m \sim 6\) pc. For GJ 1157, \(V_r = 42 \pm 1.1\) km/s [36], which yields \(d_m > 4\) pc, appreciably different from the values in Table 1.

The next five stars in Table 1 — **SOZ 3A, G 99–049, GJ 729, GJ 1061, and CN Leo — have more or less reliable radial velocities. As we can see from Table 3, their radial velocities were taken from sources other than the RAVE catalogs.

Table 3 gives the physical characteristics of the stars. The masses of the M dwarfs were estimated using the data of [40]. The spectral classification of L 87–10 is known with large uncertainty (it is not included in the standard set of data in the SIMBAD electronic database). We estimated its spectral type to be M4 based onits position on a color–absolute magnitude diagram [20,26] and the color index V–Ks=0.868. It’s spectral type is given as M5 in [41].

Three stars were considered earlier in [18]: GJ 3379 (G 99–049), GJ 3323 (LHS 1723), and SDSS J1416+1348 (**SOZ 3A). In our current study, we adopted more reliable values for the trigonometric parallaxes and radial velocities of GJ 3379 (G 99–049) and GJ 3323 (LHS 1723), compared to those used in [18]. However, the derived approach parameters for these two stars virtually coincide with those obtained earlier.
Table 3: Additional characteristics of the stars

| No. | Star        | Spectral type | Mass, $M_{\odot}$ | Source of $V_r$ | Source of $\mu, \pi$ |
|-----|-------------|---------------|-------------------|----------------|---------------------|
| 1   | L 87–10    | ~M4           | 0.2               | RAVE4          | [30]                |
| 2   | LHS 3583   | M2.5          | 0.5               | RAVE4          | [31]                |
| 3   | GJ 4274    | M4.5Ve        | 0.2               | RAVE4          | [29]                |
| 4   | ** SOZ 3A  | L7+T7.5       | < 0.08            | [32]           | [29]                |
| 5   | LHS 1351   | M2.5          | 0.5               | RAVE4          | [31]                |
| 6   | LEHPM 4771 | M4.5          | 0.2               | RAVE4          | [30]                |
| 7   | LHS 500    | M5            | 0.17              | RAVE4          | [25]                |
| 8   | G 99-049   | M3.5Ve        | 0.3               | [28]           | [28]                |
| 9   | GJ 1157    | M4            | 0.2               | RAVE4          | [23]                |
| 10  | GJ 729     | M3.5Ve        | 0.3               | [45]           | [28]                |
| 11  | GJ 1061    | M5.5V         | 0.15              | [40]           | [29]                |
| 12  | CN Leo     | M5.0Ve        | 0.17              | [44]           | [29]                |

The situation for **SOZ 3A is different. Previously, only a photometric distance estimate was available ($d = 8.0 \pm 1.6$ pc), and other values for the component proper motions and a substantially different radial velocity ($V_r = -42 \pm 5$ km/s) were used. The approach parameters $d_m = 1.24 \pm 0.65$ pc and $t_m = 186 \pm 44$ thousand years were obtained for this star in [18]; these differ substantially from the values presented in Table 1. **SOZ 3A has a known companion, ULAS J141623.94+134836.3, which is separated from the primary of the system by about 75 AU. The companion was detected from the similarity of its proper motions to those of the primary [42]. At present, the system is only a suspected binary. Therefore, long spectral observations of these stars aimed at determining their orbital characteristics and the systemic radial velocity would be helpful.

The stars L 87–10 and LHS 3583 have a high probability $P$ of penetrating into the vicinity of the cometary Oort cloud. We constructed 10 000 model orbits for these stars. Since the nominal random uncertainties in the input data are small, the cloud of model orbits for each star occupies a very compact region in the $d - t$ diagram. L 87–10 always falls in the vicinity of the Oort cloud, $d_m < 0.485$ pc, and has the probability $P = 10000/10000 = 1.0$ (the ratio of the number of orbits that fall in the vicinity of the Oort cloud to the total number of model orbits). Applying the same approach for the star LHS 3583 yields $P = 0.999$. We assumed their masses to be approximately $0.2M_{\odot}$ and $0.5M_{\odot}$, respectively; i.e., lower than the mass of GJ 710. The values of $d_m$ derived for these stars do not differ strongly from the value for GJ 710, $d_m = 0.31$ pc.

On the other hand, the masses of L 87–10 and LHS 3583 differ by a factor of two. It is interesting to compare their possible gravitational influence on objects in the Oort cloud. To do this, we can use the approach of [43] to estimate the radius of the sphere of influence of the passing star Ra (the gravitational attraction of the star dominates inside this sphere):

$$R_a = \frac{d_m}{1 + \sqrt{M_{\odot}/M_*}}$$

where $M_{\odot}$ is the mass of the Sun and $M_*$ the mass of the star. We then calculated the
distance from the Sun to the boundary, \( D_0 = d_m - R_a \), beginning from which the gravitational influence of the star on the comet dominates. As a result, we found \( D_0 = 0.19 \text{ pc} \) for L 87–10 \((M_* = 0.2M_\odot, d_m = 0.27 \text{ pc})\) and \( D_0 = 0.25 \text{ pc} \) for LHS 3583 \((M_* = 0.2M_\odot, d_m = 0.27 \text{ pc})\). The boundary \( D_0 \) lies inside the Oort cloud for both stars. Moreover, this result indicates that, in spite of the difference in mass, the gravitational influence of L 87–10 can extend to a closer vicinity of the Sun than the influence of LHS 3583.

Guided by the results of numerical simulations of variations of the parameters of cometary orbits after a close flyby of a star such as GJ 710 obtained in \([9, 16]\), we can conclude that the passage of the stars L 87–10 and LHS 3583 near the solar system may not have significant visible consequences (in the sense that it is difficult to distinguish a flux of comets created by the action of Galactic tides on a flux initiated by the flyby of one of these stars). The times for their close approaches with the Sun are shorter than for GJ 710. The difference in the flyby times is clearly visible, for example, from a comparison of the figure presented here and \([10, \text{Fig. 2}]\).

Our list also contains stars with more reliable (in a systematic sense) radial velocities. Of these, the closest approach is predicted for the low-mass system **SOZ 3A, for which an encounter with the solar orbit at a minimum distance of \( 0.72 \pm 0.11 \text{ pc} \) is expected at an epoch \( 103 \pm 44 \text{ thousand years} \) in the future. The probability of penetrating into the region of the Oort cloud was estimated from an analysis of the 10 000 model orbits; due to the fairly large random uncertainties in the input data, this probability is nonzero, \( P = 115/10000 = 0.115 \).

**CONCLUSION**

We have carried out a search for stars that have approached or will approach the solar system to distances of less than 2 pc. We compiled an initial list containing kinematic data for 175 stars. The proper motions and trigonometric parallaxes of these stars were taken from a series of publications by the RECONS consortium via the CTIOPI program. The radial velocities of all of these stars were taken from various literature sources. A substantial number of the stars have radial velocities from the RAVE4 catalog, making it possible for many stars to analyze their space velocities for the first time.

All these stars are located within 30 pc of the Sun, and are low-mass dwarfs of spectral types M, L, and T. Most of these stars have large proper motions. However, there are essentially no stars from the HIPPARCOS and Tycho-2 catalogs, making it possible for many stars to analyze their space velocities for the first time.

We traced the position of each star relative to the solar orbit over a time interval from \(-1\) to \(+1\) million years. We have identified for the first time six stars that may approach the solar system to distances of less than 1 pc.

Two stars have high probabilities of penetrating into the region of the cometary Oort cloud. The first of these, L 87–10, is predicted to approach to a minimum distance of \( d_m = 0.27 \pm 0.01 \text{ pc} \) at epoch \( t_m = 14 \pm 1 \text{ thousand years} \). For the second, LHS 3583, \( d_m = 0.42 \pm 0.02 \text{ pc} \) and \( t_m = -11 \pm 1 \text{ thousand years} \). However, the radial speeds of these stars exceed 500 km/s, since they were obtained from spectra with very low quality, which could contain appreciable errors.

Our list also includes stars with more reliable radial velocities. One example is the low-mass system **SOZ 3A (the primary SDSS J1416+1348 and the secondary ULAS
J141623.94+134836.3), for which an encounter with the solar orbit at a minimum distance of $0.72 \pm 0.11$ pc at the epoch $103 \pm 44$ thousand years is possible in the future.

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