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## Orbital migration of the planetary companion of 51 Pegasi to its present location

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**THE recent discovery<sup>1</sup> and confirmation<sup>2</sup> of a possible planetary companion orbiting the solar-type star 51 Pegasi represent a breakthrough in the search for extrasolar planetary systems. Analysis of systematic variations in the velocity of the star indicate that the mass of the companion is approximately that of Jupiter, and that it is travelling in a nearly circular orbit at a distance from the star of 0.05 AU (about seven stellar radii). Here we show that, if the companion is indeed a gas-giant planet, it is extremely unlikely to have formed at its present location. We suggest instead that the planet probably formed by gradual accretion of solids and capture of gas at a much larger distance from the star ( $\sim 5$  AU), and that it subsequently migrated inwards through interactions with the remnants of the circumstellar disk. The planet's migration may have stopped in its present orbit as a result of tidal interactions with the star, or through truncation of the inner circumstellar disk by the stellar magnetosphere.**

The first argument against the *in situ* formation of a planetary companion is based on models of the nebular disks<sup>3</sup> that are known to exist around young stars<sup>4</sup>. The standard picture of the formation of a giant planet involves the coagulation and accretion of small particles of ice and rock in the disk<sup>5</sup> until a core of about 15 Earth masses is built up; then gas, composed mainly of H and He, is accreted from the disk<sup>6</sup>. Standard disk models show that at 0.05 AU the temperature is about 2,000 K, too hot for the existence of any small solid particles. An alternative formation model<sup>7</sup> involves a massive disk, whose self-gravity is comparable to that of the central object, in which a gaseous subcondensation could form by contraction under its own gravity. But recent detailed calculations of such massive disks<sup>8</sup> indicate that they tend to form spiral arms and to transfer mass into the central star instead of fragmenting into subcondensations.

A second problem with the formation of a planet at 0.05 AU is that although the present evaporation rate of the planet is negligible, this effect would have been of major importance in the past. At 0.05 AU, the companion's effective temperature, due to stellar irradiation, is  $\sim 1,300$  K. In order to determine the planetary radius  $R_p$  in the presence of such heating, we calculated the evolution of objects in the mass range  $M_p = 1\text{--}10 M_J$  (jovian masses) using a standard stellar structure code<sup>9,10</sup> with a non-ideal interior equation of state<sup>11</sup>. The rotation of the planet is almost certainly tidally locked<sup>12</sup> so that the same hemisphere always faces 51 Peg. We assume that atmospheric motions and convection in

the interior redistribute the heat so that the dark side and the bright side have nearly the same temperature.

In Fig. 1 we show the evolution of  $R_p$  for various  $M_p$ . At 8 Gyr, the estimated age of 51 Peg,  $R_p = 8.3 \times 10^7$  m for  $1 M_J$ , not much larger than the present radius of Jupiter ( $7.0 \times 10^7$  m). For these values, the escape velocity of a hydrogen atom is 12 times larger than the mean thermal speed, and a simple calculation of the Jeans escape rate<sup>13</sup> shows that evaporation is negligible. A further process to be considered is hydrodynamic escape<sup>14</sup> in which ultraviolet and X-ray radiation from the star are absorbed by hydrogen atoms in the planetary atmosphere and drive a planetary wind. A rough estimate, based on the observed X-ray flux of young stars<sup>14</sup>, shows that the effect of this process is also negligible. Thus the planet at present is quite safe against evaporation. The evaporation of a low-mass star or brown dwarf, another proposed explanation<sup>15</sup> for the existence of the companion, would be even more difficult because the object would have a much higher surface gravity. But during the early history of a planet<sup>6</sup> its radius is a factor of ten or more larger than the present radius, so the escape speed becomes much less and both evaporation mechanisms, along with ablation by the stellar wind, will prevent formation.

We propose that the companion was formed several AU away from the star through the standard process. Recent detailed calculations<sup>16</sup> for the accretion of Jupiter at 5 AU have shown that it is possible for that planet to build well before the nebula dissipates. The protoplanet interacts tidally with the disk during its growth<sup>17</sup>. Let  $\nu$  be the disk viscosity,  $M_*$  the stellar mass,  $\omega$  the orbital frequency, and  $r_n$  the distance from the star at which the planet formed. If  $M_p \gtrsim 40\nu M_*/(\omega(r_n)r_n^2)$  when its tidal radius,  $(M_p/3M_*)^{1/3}r_n$ , exceeds  $H$  (the vertical scale height of the disk), the protoplanet induces the formation of a gap<sup>18,19</sup> in the disk near  $r_n$  so that growth of the planet stops. Standard disk models<sup>3</sup> give  $H(r) \approx 0.1r$ , where  $r$  is the distance from the star. The disk evolves viscously on a timescale  $\tau_v \approx r_d^2/\nu$  which is inferred to be  $\sim 5 \times 10^6$  yr from infrared observations<sup>20</sup>. The effective radius  $r_d$  which contains most of the disk mass observed in the infrared is<sup>4</sup>  $\sim 100$  AU. Applying these estimates to the gap formation conditions, we find  $M_p \approx M_J$ .

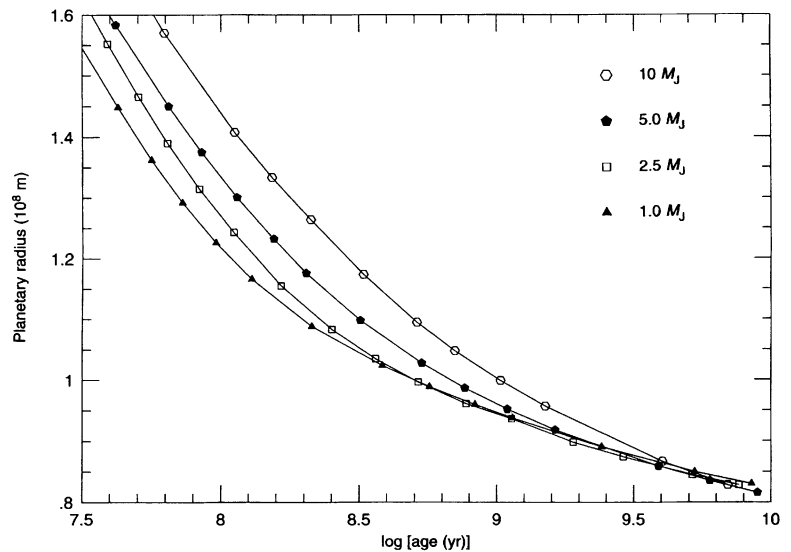
After the gap formation, angular momentum transfer continues and the protoplanet undergoes orbital migration coupled to the viscous evolution of the disk<sup>21,22</sup>. The orbital radius of the planet ( $r_p$ ) and that of the gap (both are still embedded in the disk) decrease on the timescale<sup>22,23</sup> of  $\tau_v$ . The planet essentially follows the material of the inner disk as it evolves towards the star. We now propose two possible mechanisms which suggest that this migration can terminate at  $\sim 0.05$  AU and that the planet will not plunge into 51 Peg.

**Mechanism 1.** As the planet approaches 51 Peg, tidal friction can induce angular momentum exchange between the planet's orbital motion and the spin of the star. If  $R_*$  is the stellar radius and  $P$  the orbital period of the planet, the timescale for tidal evolution is<sup>12</sup>

$$\tau_t = r_p \left( \frac{dr_p}{dt} \right)^{-1} = \frac{P}{9\pi} \left( \frac{r_p}{R_*} \right)^5 \left( \frac{M_*}{M_p} \right) Q. \quad (1)$$

We estimate the dissipation parameter  $Q_* = 1.5 \times 10^5$  for a main sequence star based on the observation<sup>24</sup> that the orbits of short-period pre-main-sequence binary stars and the main-sequence binary stars in the Pleiades cluster are circularized for  $P \lesssim 5$  and 7 days, respectively. As young stars rotate more rapidly than their main-sequence counterparts<sup>25</sup>, we assume that 51 Peg was rotating rapidly enough that the co-rotation point  $\tau_{CR}$  (the distance from the star where an orbiting object has the same angular frequency as the stellar rotation) was inside 0.05 AU. The tidal effect then results in outward migration of the planet. Thus there may exist a radius  $r_c$  where the protoplanet's radial migration was halted by a balance between the inward push on it by the disk and the outward push from 51 Peg. At that point, the angular momentum transfer

FIG. 1 Planetary radius as a function of log age for objects (bottom trace to top trace) of masses 1, 2.5, 5 and  $10 M_J$ . The calculation assumes that the planet migrated to its present position during its first ten million years of existence. The plot shows the subsequent evolution, during which the orbit of the planet was stationary and it was heated by a central star whose luminosity was constant in time. For this evolutionary history, evaporation is not important.



equilibrium throughout the disk<sup>19</sup> implies  $\tau_v \approx \tau_r$  such that  $r_c \equiv (9\pi\tau_r M_p / P_* Q_* M_*)^{2/13} R_*$ , where  $P_*$  is the keplerian orbital period at  $R_*$ . Based on an estimate<sup>26</sup> of  $R_* = 4R_\odot$  (where  $R_\odot$  is the solar radius) during its early history, we find that this equilibrium can be established at 0.05 AU during the early epoch of 51 Peg.

But this equilibrium is only temporary. The disk material between the planet and the star will accrete onto the latter, leaving the planet with the remaining disk outside its orbit. The disk's surface density adjusts until a quasi-equilibrium state is attained in which the angular momentum flux is approximately constant with distance from the star. At this stage the planet's equilibrium radius is determined by the condition that the star's tidal torque on it,  $M_p r_p^2 \omega_p / \tau_r$ , is balanced by the angular momentum flux through the disk,  $\sim M_d r_d^2 \omega_d / \tau_v$ , where  $\omega_d$  is a mean angular frequency of the disk and  $M_d$  is its mass. For  $R_* = 4R_\odot$  we find that  $r_c \approx 0.03(M_p/M_d)^{1/6}(\tau_v/5 \times 10^6 \text{ yr})^{1/6}$  AU. If the disk then dissipates sufficiently so that its mass  $M_d \approx M_p$  and its evolution timescale lengthens so that  $\tau_v \approx 10^8$  yr, then  $r_c$  could be close to the present orbital position of the planet. The dissipation must occur before the star contracts substantially ( $<10^7$  yr) or spins down ( $>10^8$  yr). In view of the rather precise timing and the relatively large  $R_*$  needed for this mechanism to work, we consider an alternative, as follows.

**Mechanism 2.** The spin periods of classical T Tauri stars are clustered<sup>27</sup> around 8 days, longer than those of the weak line T Tauri stars. One explanation for the 8-day periods is that the spin rate is controlled by coupling between the stellar magnetosphere and the disk<sup>28</sup>. The presence of the magnetosphere would also clear<sup>29</sup> the inner disk out to a point slightly less than  $r_{CR}$  (0.08 AU for an 8-day period). Once the planet has spiralled in to  $r_p = 0.05$  AU, angular momentum exchange between it and the disk occurs only via the 2:1 resonance at a reduced (by  $\sim M_p/M_*$ ) rate<sup>17,30</sup>. Because  $r_p < r_{CR}$ , the stellar tidal effect also continues to induce an inward migration. But as long as  $R_* < 3R_\odot$ , consistent with evolutionary tracks<sup>26</sup>,  $\tau_r$  is larger than the stellar contraction timescale, and the migration effectively stops near 0.05 AU.

After this time, in either case,  $\tau_r$  and  $\tau_v$  increase rapidly because the star contracts on a relatively short timescale, and the disk dissipates. During its contraction to the main sequence, 51 Peg may have spun up, if it conserved angular momentum, but once it reached the main sequence, the star would have spun down<sup>31</sup> because of angular momentum loss via stellar wind. Eventually in both cases  $r_p$  becomes less than  $r_{CR}$  and  $R_* \approx R_\odot$ , causing the

companion to migrate inwards on the timescale  $\tau_r \approx 14 \sin i_p$  Gyr, which is much longer than the age of the star for all reasonable values of the inclination angle  $i_p$  between the normal to the orbital plane and the line of sight. This is the configuration we observe today. The requirement that the tidal migration timescale ( $\tau_r$ ) be large compared with the life span of a typical solar-type star is a further piece of evidence that supports the interpretation that the companion is a planet with  $M_p \approx M_J$  rather than a more massive object.  $\square$

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