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

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The recent discovery[1] and confirmation[2] of a possible low mass companion to the G dwarf star 51 Pegasi mark a milestone in the search for indicate the presence of a companion of approximately one Jupiter mass travelling in a nearly circular orbit at 0.05 AU, with a period of 4.23 days. Accepting the interpretation that this object is a gas-giant planet, we show in this paper that it is extremely unlikely that such a planet could have formed at its present location. We suggest that the planet could have formed, by gradual accretion of solids and capture of gas, at a much larger distance, say 5 AU, that it migrated inward through interactions with the remnants of the circumstellar disc, and that the migration stopped as a result of tidal interaction with the star or truncation of the inner disc by a magnetic field.

The first argument against the *in situ* formation of a companion is based on models of the nebular discs[3] which are known to exist around young stars[4]. The standard picture of the formation of a giant planet involves the coagulation and accretion of small particles of ice and rock in the disc[5] until a core of about 15 earth masses is built up; then gas, composed mainly of H and He, is accreted from the disc[6]. Standard disc models show that at 0.05 AU the temperature is about 2000 K, too hot for the existence of any small solid particles. An alternative formation scenario[7] involves a massive disc, whose self-gravity is comparable to that of the central object, in which a gaseous subcondensation could form by contraction under its own gravity. However, recent detailed calculations of such massive discs[8] 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 ≈ 1300 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 $M_p = 1$–$10\ M_J$ (Jovian masses) using a standard stellar structure code[9,10] with a non-ideal interior equation of state[11]. The rotation of the planet is almost certainly tidally locked[12] 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 Figure 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 (7.0×10^7 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[13] shows that evaporation is completely negligible. A further process to be considered is hydrodynamic escape[14] 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[14], 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[15] for the existence of the companion, would be even more difficult because the object would have a much higher surface gravity. However during the early history of a planet[6] 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[16] for the accretion of Jupiter at 5 AU have shown it is possible to build that planet well before the nebula dissipates. The protoplanet interacts tidally with the disc during its growth[17]. Let ν be the disc viscosity, $M_\star$ the stellar mass, ω the orbital frequency, and r_n the distance from the star at which the planet formed. If $M_p \gtrsim 40\nu M_\star/(\omega(r_n)r_n^2)$ when its tidal radius, $(M_p/3M_\star)^{1/3}r_n$, exceeds H (the vertical scale height of the disc), the protoplanet induces the formation of a gap[18,19] in the disc near r_n so that growth of the planet terminates. Standard disc models[3] give $H(r) \sim 0.1r$. The disc evolves viscously on a timescale $\tau_\nu \sim r_d^2/\nu$ which is inferred to be $\sim 5 \times 10^6$ yr from infrared observations[20]. The effective radius r_d which contains most of the disc mass observed in the infrared is[4] ~ 100 AU. Applying these estimates to the gap formation conditions, we find $M_p \sim M_J$.

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

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 $R_\star$ is the stellar radius and P the orbital period of the

planet, the time scale for tidal evolution is[12]

$$\tau_r = r_p \left(\frac{dr_p}{dt}\right)^{-1} = \frac{P}{9\pi}\left(\frac{r_p}{R_\star}\right)^5 \left(\frac{M_\star}{M_p}\right) Q_\star. \tag{1}$$

We estimate the dissipation parameter $Q_\star = 1.5 \times 10^5$ for a main sequence star based on the observation[24] 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. Since young stars rotate more rapidly than their main-sequence counterparts[25] we assume that 51 Peg was rotating rapidly enough so that the corotation point r_{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 disc and the outward push from 51 Peg. At that point, the angular momentum transfer equilibrium throughout the disc[19] implies $\tau_\nu \sim \tau_r$ such that $r_c \equiv (9\pi\tau_\nu M_p/P_\star Q_\star M_\star)^{2/13} R_\star$ where $P_\star$ is the Keplerian orbital period at $R_\star$. Based on an estimate[26] of $R_\star = 4R_\odot$ during its early history, we find that this equilibrium can be established at 0.05 AU during the early epoch of 51 Peg.

However, this equilibrium is only temporary. The disc material interior to the planet will accrete onto the star, leaving the planet with the remaining disc outside its orbit. The disc'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 disc, $\approx M_d r_d^2 \omega_d / \tau_\nu$, where ω_d is a mean angular frequency of the disc and M_d is its mass. For $R_\star = 4 R_\odot$ we find $r_c \approx 0.03 (M_p/M_d)^{1/6} (\tau_\nu / 5 \times 10^6 \mathrm{yr})^{1/6}$ AU. If the disc then dissipates sufficiently so that its mass $M_d \approx M_p$ and its evolution time scale lengthens so that $\tau_\nu \sim 10^8$ 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 $R_\star$ needed for this mechanism to work, we consider an alternative:

2. The spin periods of classical T Tauri stars (CTTS) are clustered[27] 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 disc[28]. The presence of the magnetosphere would also clear[29] the inner disc 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 disc occurs only via the 2:1 resonance at a reduced (by $\sim M_p/M_\star$) rate[17,30]. Since $r_p < r_{CR}$ the stellar tidal ef-

fect also continues to induce an inward migration. However as long as $R_\star < 3R_\odot$, consistent with evolutionary tracks[26], τ_r is larger than the stellar contraction timescale, and the migration effectively stops near 0.05 AU.

After this time, in either case, τ_r and τ_ν increase rapidly because the star contracts on a relatively short time scale, and the disc 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[31] because of angular momentum loss via stellar wind. Eventually in both cases r_p becomes less than r_{CR} and $R_\star \approx R_\odot$, causing the companion to migrate inward 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 i_p. This is the configuration we observe today. The requirement that the tidal migration timescale (τ_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 $M_p \sim M_J$ rather than a more massive object.

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Figure Captions

Fig. 1 Planetary radius (in 10^8 m) as a function of log time (in yr) for objects (bottom to top) 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.

Figure 1