FORMING A JUPITER-LIKE COMPANION FOR 51 PEGASI. A. P. Boss, DTM, Carnegie Institution of Washington, 5241 Broad Branch Road N.W., Washington DC 20015-1305.

The recent discovery of a likely Jupiter-mass planetary companion to the star 51 Pegasi was startling because the 4.23 day period of the companion implies an orbital separation of only 0.05 AU from 51 Pegasi. If the companion is a gas giant planet formed by the mechanism believed to be responsible for the formation of Jupiter, then the companion to 51 Pegasi could not have formed at its present distance from 51 Pegasi. Radiative hydrodynamical models of protoplanetary disks show that any Jupiter-like planet must have formed at a distance from 51 Pegasi similar to that of Jupiter from our Sun, and then been dragged much closer to 51 Pegasi. Gravitational interactions with a long-lived protoplanetary disk provide an attractive means for accomplishing this planetary migration. Such a scenario implies that any Earth-like planets that also formed around 51 Pegasi disappeared into the central star long ago.

INTRODUCTION.

51 Pegasi is a nearby G-type star very similar to our Sun which has been shown [1] to exhibit a periodic Doppler shift of its spectral lines consistent with the presence of an orbiting companion. The companion's mass lies in the range of one half to a few times the mass of Jupiter, assuming the orbit is nearly edge-on relative to our line of sight. This appears to be the first confirmed discovery of a planetary-mass companion to a solar-type star. However, the orbital period of the companion is quite short, 4.23 days (versus 11.9 years for Jupiter) – the companion orbits about 100 times closer to 51 Peg than Jupiter does to our Sun. In spite of a high surface temperature, a gas giant planetary companion to 51 Peg apparently is stable at 0.05 AU [2].

The leading theory of giant-planet formation rules out forming a Jupiter-like planet 0.05 AU from 51 Pegasi. The giant planets of our solar system are believed to have formed through a two-step process [3,4]. First, collisions within a huge swarm of kilometer-sized planetesimals orbiting the young Sun beyond 4 AU led to the formation of a massive planetary embryo. By the time the mass of the planetary embryo reaches about ten times that of the Earth, the embryo is massive enough that its distended atmosphere of hydrogen and helium gas suddenly collapses inward [5,6]. More gas from the disk accretes onto the protoplanet, rapidly increasing its mass toward its final value.

Formation of a gas giant planet thus requires as a first step the collisional growth of a $\sim 10M_{\oplus}$ planetary embryo. Because icy material was two to three times more prevalent in the solar nebula than was rocky material, such massive planetary embryos are most likely to form where both icy and rocky planetesimals existed, i.e., in the relatively cool outer regions where the midplane disk temperature is less than the ice sublimation temperature of $\approx$ 160 K. Massive planetary embryos are also more likely to form in the outer disk because with a surface density profile like $\sigma \propto r^{-1/2}$, the disk mass within an annulus increases with disk radius. Forming a Jupiter-mass planet directly from refractory solids at 0.05 AU would require a disk much more massive than the central star, if present models of planetary accumulation [7] are applicable.

RESULTS.

The ice condensation radius in a protoplanetary disk thus sets a lower limit on the radius at which Jupiter-like planets could form. The thermal structure of quasi-equilibrium protoplanetary disks has been calculated with a two dimensional radiative hydrodynamics code and used to predict the minimum orbital radius of Jupiter-like planets around low-mass stars [8] when planetary migration is negligible. Recently, a more comprehensive set of protoplanetary disk models has been computed [9], with a wide range of possible disk parameters being considered. Even with fairly large changes in the disk properties, the ice condensation radius never falls closer than a few AU from a solar-mass central star (see Figure 1). Hence icy planetesimals (and massive planetary embryos) cannot form at the inferred radius of 51 Peg's companion.

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CONCLUSIONS.

Because a Jupiter-like planet cannot form any closer than about 3 AU from a star like 51 Peg, the inferred orbital radius of 0.05 AU for 51 Peg's companion means that if the companion is a gas giant planet, it must have moved inward a considerable distance after it was formed. The most likely means for accomplishing this orbital decay is through interactions between the Jupiter-mass planet and the gas of the protoplanetary disk [10]. Jupiter-mass planets can raise spiral density waves in the protoplanetary disk, which in turn can remove angular momentum from the planet and cause it to spiral inward. Any planets that had formed between the Jupiter-mass planet and 51 Peg would have been lost in this scenario – they would have spiralled into 51 Peg itself and been lost. In the case of our solar system, the disk gas must have disappeared soon after Jupiter grew to its present mass, well before our planetary system could spiral into the Sun. This major difference between the lifetimes of the solar nebula and of 51 Peg's disk is consistent with astronomical evidence for greatly varying lifetimes (ranging from about 10^5 yrs to 10^7 yrs) for protoplanetary disks [11].

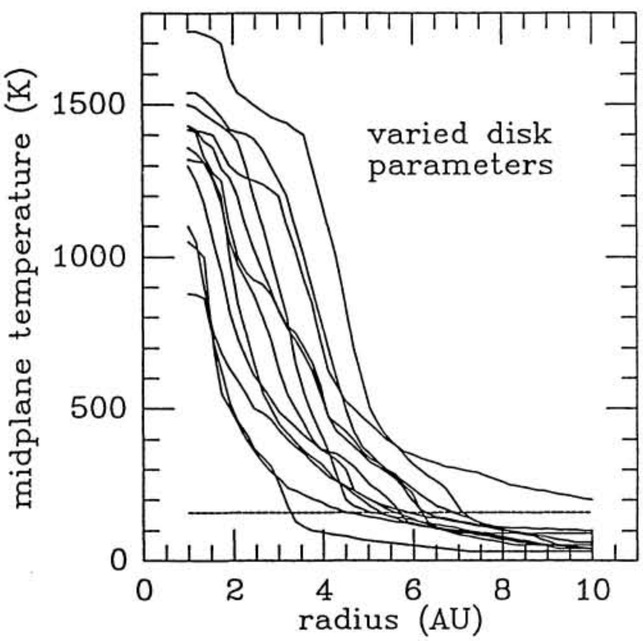

Figure 1. Midplane temperatures as a function of radius for 12 protoplanetary disk models with varied disk masses, disk mass accretion rates, radial density profiles, opacities, and turbulent viscosity parameters [9]. Icy planetesimals are only stable ($T_m < 160$ K = dashed line) outside a few AU in these models.

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