EXTENT OF POLLUTION IN PLANET-BEARING STARS

S.-L. Li,1,2 D. N. C. Lin,2,3 and X.-W. Liu1,3

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ABSTRACT

Preliminary observational findings suggest a deficiency of short-period hot Jupiters around post-main-sequence (G giant and subgiant) stars, although the total fraction of them with known planets appears to increase with stellar masses. Here we consider the possibility that some very close-in gas giants or a population of rocky planets may have either undergone orbital decay or been engulfed by the expanding envelope of their intermediate-mass host stars. If such events occur during or shortly after those stars’ main-sequence evolution when their convection zone remains relatively shallow, their surface metallicity would be significantly enhanced by the consumption of one or more gas giants. During the evolution of a star with a given mass and internal metallicity, a surface temperature-luminosity relation maps its evolutionary track. Therefore, we can infer the internal metallicity with the observables including the star’s brightness, color, parallax, and the planet’s transit light curve. Whether a star is polluted is then determined by the comparison between the inferred internal metallicity and the observed surface metallicity. As an example, we consider HD 149026, possibly a post-main-sequence star, and suggest its observed high (nearly twice solar) metallicity may be confined to its surface layer as a consequence of pollution by the accretion of a gas giant or a population of smaller-mass rocky planets. We show that the extent of pollution can be inferred directly from high-precision distance determinations, radial velocity, and transit light curves.

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1. INTRODUCTION

In the radial velocity search for planets around nearby main-sequence FGK dwarf stars, it is well established that the detection probability of Jupiter-mass gas giant planets increases rapidly with the metallicity of the target stars (Gonzalez 1997; Fischer & Valenti 2003; Santos et al. 2003). There are two scenarios for this observational correlation: (1) gas giant planets are preferentially formed around metal-rich stars (Ida & Lin 2005b), or (2) the host stars of planetary systems are polluted by infalling planets (Sandquist et al. 1998, 2002).

The first (threshold-core-accretion) scenario is based on the assumption that the nascent disks of known extrasolar planets had the same initial metallicity as their host stars because the entire material contents of these stars were accreted via these disks. Heavy elements first condense into grains which not only evolve through cohesive and disruptive collisions with each other, but also undergo orbital decay as a consequence of gas drag. The efficiency of grain-planetesimal conversion increases with the metallicity of the disk because both collision rate and orbital decay timescale also increase with the disk metallicity (Supuver & Lin 2000). Gravitational instability in dust layers is also more likely to occur in metal-rich disks (Sekiya 1983; Youdin & Shu 2002), albeit the threshold metallicity for the onset of gravitational instability may be considerably larger than those of the most metal-rich stars (Garaud & Lin 2004). Nevertheless, the critical conditions for planetesimal formation and retention may be preferentially satisfied near the snow line and the ionization front because grains are effectively trapped at these regions.

(Kretke & Lin 2007; Kretke et al. 2008). In metal-rich disks, the localized accumulation of the planet-building material enhances the growth rate of planetesimals, increases the asymptotic isolation mass of protoplanetary embryos around metal-rich stars, suppresses the efficiency of their type I migration, and therefore promotes the emergence of gas giant planets (Ida & Lin 2005a, 2008a, 2008b).

Although the elevated metallicity of planet-bearing solar-type stars can be easily accounted for by the threshold-core-accretion scenario, pollution at some level is unavoidable unless the planet formation process is highly efficient in retaining all the residual planetesimals. There are many potential avenues which may lead to planetesimal or protoplanet accretion by their host stars.

1.1. Possible Avenues for Stellar Pollution

The epoch of planet formation.—During the early stage of protoplanet formation, planetesimals and protoplanets undergo type I and II orbital migration, respectively, as they interact with their nascent disks (Goldreich & Tremaine 1980; Ward 1984; Lin & Papaloizou 1986). However, rocky planetary embryos’ orbital decay may be quenched as they approach the rim of an inner disk cavity, which is cleared by the magnetosphere of their host stars (Koenigl 1991), or the inner boundary of the dead zone where the ionization fraction at the disk midplane is marginal for magnetorotational instability (MRI) to effectively induce angular momentum transfer in the gas (Gammie 1996; Hirose et al. 2006; Kretke et al. 2008). At these regions, local maxima in the pressure distribution lead to super-Keplerian gas motion so that the net rate of angular momentum exchange between the embryo and the disk is nullified by a balance of embryos’ torque on the disk gas at their Lindblad and corotation resonances (Masset 2001). As embryos accumulate in the proximity of their host stars, their close encounters with each other and dynamical relaxation (Terquem & Papaloizou 2007) can induce many to merge.
with each other as well as to strike their host stars (Morbidelli et al. 2008).

The discovery of close-in gas giants supports the conjecture that they can form far away from their host stars and undergo type II migration to their present-day location (Lin & Papaloizou 1986; Ida & Lin 2004). This orbital decay may also be halted when such planets enter into the magnetospheric cavity around their host stars (Lin et al. 1996; Laine et al. 2008). During the course of their dynamical evolution, these destined “hot Jupiters” would not only interact with the stalled embryos at the inner disk edge but also capture, through their mean motion resonances, any residual planetesimals along their paths and herd them to the proximity of their host stars (Zhou et al. 2005). Through close encounters, many planetesimals and embryos may be scattered into the stellar envelope. Some gas giants may also migrate directly into host stars with relatively weak magnetic fields because the stellar magnetospheric cavity is too closely confined to the stellar surface.

Accretion of young planets and residual planetesimals.—In disks with modest amounts of gas, gas giants may not migrate extensively prior to the depletion of the disk gas (Ida & Lin 2004). Indeed, most known extrasolar planets have periods longer than 1 yr. However, in systems which contain eccentric gas giants, the disk depletion process leads to a sweeping secular resonance (Ward et al. 1976; Heppenheimer 1980; Ward 1981; Nagasawa & Ida 2000; Nagasawa et al. 2001), which excites the eccentricity of the residual planetesimals. Subsequent drag by the remaining tenuous disk gas can induce these planetesimals to migrate toward their host stars (Nagasawa et al. 2005; Zhou et al. 2005) and excite the gas giants’ eccentricities (Nagasawa & Lin 2005). Planetesimal clearing by known gas giants’ sweeping secular resonances would be much less efficient if the disk gas depletion proceeded rapidly.

After the gas is severely depleted over several megayears, long-term dynamical instabilities can also lead to orbit crossing and close encounters which can scatter the residual planetesimals and planets to migrate over considerable distances (Murray et al. 1998; Ida et al. 2000; Chambers & Wetherill 2001). In the outer solar system, the long-term perturbation of Jupiter and Saturn has resulted in the outward scattering of most residual planetesimals and the formation of the Kuiper belt objects and Oort Clouds. Nevertheless, at least a fraction of this population (a few $M_\oplus$) are also scattered inward to form the terrestrial planets and to be accreted by the Sun (Murray et al. 2001; Murray & Chaboyer 2002). Due to observational selection effects, most of the known extrasolar planets have periods less than those of the gas giants in the solar system. In these relatively compact planetary systems, the inward-scattered fraction is likely to be larger than that in the solar system because close planetary encounters are less able to provide an adequate dynamical boost to the planetesimals’ orbital energy for them to overcome the steeper stellar gravitational potential. The determination of this fraction is particularly important in the calibration of the efficiency of the planet formation process and the assessment on the fraction of stars which contain gas giant planets.

Protracted heavy-elemental accretion during the long-term dynamical evolution of planetary systems.—Another motivation to search for evidences of planet consumption is the theoretical inference of a larger-than-observed population of close-in gas giant planets (Ida & Lin 2005a, 2008a). Although type II migration can account for the overall origin of the short-period planets, their survival is based on some assumed halting mechanisms such as planet-star interaction for those with close-in orbits and disk depletion for those with intermediate (a week to a year) periods. In this scenario, the period distribution of these planets would require the disruption of a significant fraction of gas giants which migrated to the stellar proximity.

Around systems with known close-in planets, there is an elevated possibility of several prior generation gas giants which have migrated even closer to their host stars (Bryden et al. 2000). The physical process which stalled the known gas close-in planets would be effective in, at least temporarily, retaining multiple close-in planets. There are no known multiple planet systems which contain more than one gas giant with period less than a week. These “missing” planets may either have migrated directly into their host pre-main-sequence host stars or were halted initially and then resumed their orbital decay on a much longer tidal evolution timescale. The latter scenario would imply a general decline in the fraction of stars with close-in gas giants as the systems age. Again, establishing evidence for gas giant planet consumption is important in providing valuable clues on the dynamical evolution of planetary systems.

Based on their high-precision (with $<1$ m s$^{-1}$ accuracy) radial velocity survey, Mayor et al. (2008) estimate that up to $\sim$30% of nearby solar-type stars may have “super-Earths,” i.e., rocky planets with mass $\sim 1 \mathrm{M}_\oplus$ and period less than a few days. In the core formation scenario, dynamically isolated embryos form throughout the inner regions of their nascent disks. In relatively massive disks, Earth-mass embryos formed interior to the snow line, and they are likely to migrate to the proximity of their host stars under the action of type I migration (Ward 1981; Ida & Lin 2008a). At the inner boundary of an MRI-inactive dead zone (Kretke et al. 2008) or the outer edge of the magnetospheric cavity, super-Keplerian azimuthal gas velocities, induced by local pressure maxima, would suppress type I migration (Masset et al. 2006; Zhang et al. 2008). This process leads to an accumulation of embryos which promotes the prolific emergence of super-Earths (Ida & Lin 2008b). At several AU’s from the central stars, the snow line provides another effective retention mechanism for both dusts and embryos (Kretke & Lin 2007) and promotes the formation of gas giants (Ida & Lin 2008b). Around some stars, type II migration can also lead to the formation of close-in gas giants after the emergence of these super-Earths. Under the combined influence of the close-in gas giants’ perturbation and their tidal interaction with their host stars, the super-Earths would undergo orbital decay (Zhou & Lin 2008). This scenario provides an additional potential avenue for the pollution of stars with close-in gas giants.

The eccentricities of known planets with periods longer than a week have a Rayleigh distribution ranging between zero and unity. This state can be established through dynamical instability (Zhou et al. 2007). During the subsequent relaxation (Papaloizou & Terquem 2001), some planets escape from the gravitational grip while others venture to the proximity of their host stars (Ford et al. 2001; Ford & Rasio 2006). Planets with sufficiently small pericentric distances may be tidally disrupted during their subsequent orbital circularization process (Gu et al. 2003, 2004). The metal-rich planetary debris would be accreted by their host stars.

Finally, most stars form in clusters which are eventually disrupted under Galactic tides. Stellar encounters can also lead to perturbations which can destabilize planetary systems and induce residual planetesimal bombardment onto their host stars (Adams & Laughlin 2003; Spurzem 2008).

1.2. Metallicity Enrichment of Stellar Surface

When planets and planetesimals enter the atmosphere of their host stars, they become disintegrated as a consequence
of Rayleigh-Taylor and shearing instabilities (Sandquist et al. 2002). The metal-enriched planetary debris rapidly dissolves and becomes mixed with the gas in the convective envelope near the stellar surface. However, during the epoch of planet formation, their host stars, such as the (solar mass) T Tauri and possibly the more massive Herbig Ae/Be stars, have deep convective regions. Any accreted metal-rich protoplanets during the first few mega-years after the formation of their host stars are dissolved in the stellar envelope, and the excess metals are mixed by convection and homogenized throughout the envelope.

On the timescale of ~30 Myr, the convection zone of a solar-type star is reduced to contain only the top 2% of the total stellar mass and ~100 $M_\odot$ heavy elements (Ford et al. 1999). This timescale is shorter, and the total mass of the convection zone is smaller for F than for G dwarf stars. Around G dwarfs or earlier type stars, pollution, if occurring after the stars have entered the main-sequence phase of evolution, would largely enhance the observed metallicity on their surface. The accretion of a Jupiter-like planet or a few $M_\odot$ planetesimals during the main-sequence life span of the more massive (say F) stars would enhance the metallicity of their shallow convective envelopes more significantly.

### 1.3. Existing Observational Constraints on the Pollution of Planet-bearing Solar-type Stars

A direct method to distinguish between the two scenarios for the stellar metallicity–planet bearing correlation and to quantitatively determine the extent of heavy-element pollution is to observationally deduce the metallicity dispersion among similar mass stars within a given open cluster. The observed chemical homogeneity among solar-type stars in the Pleiades and IC 4665 clusters (Wilden et al. 2002; Shen et al. 2005) places a stringent upper limit (<10 $M_\odot$) on the pure planetesimal/rocky planet accretion after they enter the main-sequence evolutionary track, if most of their masses are contained in a few relatively massive embryos. In addition, the formation of planets requires protoplanetary debris disks to retain at least comparable amounts of heavy elements (~100 $M_\odot$) as that contained in the solar system planets (Ida & Lin 2004). The observed chemical homogeneity among the cluster stars challenges this requirement. However, despite several attempts to search for planets in the Hyades (Guenther et al. 2005), only one planet has been found around one star (Sato et al. 2007). Therefore, the stringent upper limit in the metallicity dispersion does not provide sufficient information to place an upper limit on the amount of pollution onto the cluster stars.

A more subtle differential comparison is to search for any correlation between the metallicity and mass of planet-bearing field stars. Since the mass of the convective envelope of solar-type stars decreases with stellar mass, extensive pollution should lead to a correlation between the spectral type and the surface metallicity (Laughlin & Adams 1997). Among the known GK dwarf stars harboring planets, the lack of any spectral class–metallicity correlation has been cited as evidence that the late accretion of planets and planetesimals cannot account for the preferential association of planets with metal-rich stars (Fischer & Valenti 2005). Quantitatively, it limits the amount of late planetesimal/rocky planet accretion to be less than the total heavy elements contained within the smallest surface convection zone of planet-bearing stars. For planet-bearing main-sequence host stars (mostly G and K dwarfs), the mass of their convective envelope is $\approx 10^{-2} M_\odot$. So to yield any observable variations in their surface metallicity, pollution of well over 100 $M_\odot$ metals is needed after the stars have begun their main-sequence evolution.

### 1.4. Observational Tests on the Pollution of Planet-bearing G Subgiant and Giant Stars

Ideally, constraints on the extent of protracted metallicity pollution is best placed on the intermediate-mass (earlier than F8) planet-bearing stars. However, atmospheres of these stars are hotter than those of the solar-type stars, and they often have rapid spins. The former effect prevents the formation of many useful spectroscopic lines, whereas the latter introduces considerable Doppler broadening. Both effects introduce challenges to the radial velocity surveys for planetary companions around high-mass stars. Consequently, there were very few F stars in the original sample, based on which the spectral class–metallicity correlation was established.

More recently, searches for planets around massive stars have shifted to target such stars after they have evolved onto their subgiant and giant tracks and become G giant stars. During this post-main-sequence phase, the atmosphere of these stars becomes cooler with relatively slow spins. Preliminary surveys indicate that the fraction of these relatively massive G giant stars with planets may be higher than that around the solar-type G dwarf main-sequence stars (Sato et al. 2007; Johnson et al. 2007; Dollinger et al. 2007). In addition, all of these planet-bearing stars have metallicity comparable to that of the Sun. Based on the lack of any obviuous metallicity dependence in the frequency of planet-bearing G giant stars, in contrast to the well-known metallicity–planet frequency correlation among the G dwarf stars, Pasquini et al. (2007) suggest that the planetary consumption may be a major cause for this dichotomy. In this scenario, (1) the high surface metallicity among the main-sequence stars is mainly due to planet consumption, and (2) the surface metallicity of planet-bearing stars decreases during their post-main-sequence evolution as their convective envelopes steepen and become more diluted.

There are some supporting evidences for planet consumption among the G giant stars. There is an apparent lack of short-period gas giant planets around these stars despite the fact that they are much easier to detect. In contrast, several dozen known planets around main-sequence stars have periods less than 5 days, with some as short as 1 day. The post-main-sequence expansion of their host stars’ envelope, the star-planet tidal effect, may promote the orbital decay of close-in gas giants by the excitation of both Hough and inertial waves (Ogilvie & Lin 2007). If such a process can lead to the consumption of short-period gas giants, the accreted planetary debris would be retained near the surface layer above the radiative interior. Eventually, the stellar envelope engulfs the orbits of the close-in planets, and induces their orbital decay and disruption (Livio & Soker 2002). The mass contained in the convection zone of the post-main-sequence stars increases with the expansion of their photospheric radius. When these stars enter the subgiant phase, there would be sufficient mass in the convective envelope to homogenize and reduce their surface metallicity to their interior solar values. Nevertheless, between these two epochs, i.e., shortly after they have evolved off the main sequence but before they have entered the subgiant track, the prior consumption of very close-in, metal-rich gas giants or a population of rocky planets around sufficiently massive stars may lead to noticeable metallicity enhancement near their surface layers.

### 1.5. A Synopsis of the Present Paper

In this paper, we identify a planet-bearing star, HD 149026, as a transitional (between main-sequence turnoff and the subgiant branch) system. The host of this system is a post-main-sequence 1.3 $M_\odot$ star with nearly twice solar metallicity, and it has a $P = 2.7$ day period Saturn-mass planet (HD 149026b) with a
70 Earth-mass core. In a companion paper (S.-L. Li et al. 2008, in preparation), we propose that the large core structure of this planet was acquired through planetary mergers after it has migrated to the proximity of HD 149026. In this scenario, some debris material and residual planetesimals are expected to be scattered into the host star by such a close-in planet. The migration of HD 149026b may also have induced the orbital decay of planets and planetesimals along its migration path (Zhou et al. 2005). Long-term dynamical instability could also have led to planet accretion onto the host star. Based on these anticipations, we identify HD 149026 to be an ideal star to study the effect of pollution.

The present-day convection zone of HD 149026 is an order of magnitude less massive than that of the Sun (0.02 $M_\odot$). The consumption of a few Earth masses of residual planetesimals, embryos, or a metal-rich gas giant can easily increase the metallicity of this thin layer from the solar value to the observed one ([Fe/H] $\sim$ 0.36). We briefly describe the method for computing the effect of pollution in § 2. We present the impact of the stellar structure due to planetary accretion in § 3 and the effect on the stellar evolution during the main-sequence turnoff of HD 149026. We show that within the range of the present observational uncertainties, the internal [Fe/H] of HD 149026 may be comparable to that of the Sun. We also show that a surface pollution of this star may modify its post-main-sequence evolutionary track and its present-day mass-radius relation. Based on these stellar models, we outline a set of self-consistent observational tests which may be used to check the merger and stellar pollution hypothesis in § 5. This test is also important to place a more precise determination of the planetary radius and the mass of its core. Finally, we summarize our results and discuss their implications in § 6.

2. COMPUTATIONAL METHOD

We construct stellar models with the Eggleton stellar evolution code (Eggleton 1971, 1972). It is based on a one-dimensional Henyey scheme with adaptive mesh. The input physics has been updated by Pols et al. (1995) and implemented by Sandquist et al. (2002). It includes a combination of OPAL opacity for stellar interior (Iglesias & Rogers 1996) and low-temperature opacities for the surface (Alexander & Ferguson 1994), a combination of SCVH (Saumon et al. 1995) and OPAL (Rogers 1994) equations of state, and nuclear reaction rates (Bahcall et al. 1995). Chemical diffusion is included, using the method of Thoul et al. (1994). Convection is treated using the standard mixing-length theory, and semiconvective mixing is incorporated in a diffusive manner. By calibrating the solar model with the observational data of the present Sun, we obtain the ratio of mixing length to the pressure scale height $\alpha = 1.933$. We find satisfactory agreement when comparing the radius of the convection zone base of our solar model with the observed value from the solar p-mode spectrum (Christensen-Dalsgaard et al. 1991).

The code has been adapted to allow for the nonhomogeneous metallicity for polluted stellar models. In previous investigations on the effects of stellar pollution (i.e., Laughlin & Adams 1997; Ford et al. 1999; Pinsonneault 2001; Dotter & Chaboyer 2003; Cody & Sasselov 2005), stellar models are constructed based on the assumption that the high-metallicity material accreted by the star is fully mixed in the stellar convective envelope. This approximation is adequate for solar-type stars, since all debris are dissolved during their passage through the stellar outer convective layers. HD 149026 is a G0 IV star with a very shallow convective layer with a total mass $\sim$0.003 $M_\odot$ in hydrogen gas. If the surface convective layer is homogenous and has an [Fe/H] as observed, its total mass of heavy elements would amount to $\sim$10$^{-4}$ $M_\odot$, which is less than half of that contained in HD 149026b. If debris material plunges into the host star along radial orbits, modest-sized planetesimals would survive the passage through the convective layer and disintegrate in the radiative region. The amount of disrupted planetesimals in the stellar atmosphere and envelope depends on their trajectory, composition, as well as the background temperature and density distributions. In order to take into account two limiting possibilities, we adopt two simple prescriptions for the deposition of the accreted heavy elements in the polluted stellar models.

We first consider the possibility that the residual planetesimals, embryos, and ill-fated gas giants undergo a gradual orbital decay and enter the stellar envelope through the stellar atmosphere with a large azimuthal motion. In this case, even the largest embryos or gas giants will be completely disrupted in the convective layer (Sandquist et al. 2002). Thus, in our first prescription, we assume that the observed metallicity of HD 149026 applies only to its thin convective layer, whereas its interior has a solar metallicity.

In a second prescription, we consider the other possibility that pollutants strike the host star on a direct radial trajectory. This assumption would be appropriate if the debris is scattered into the stellar envelope by close encounters with the gas giant. In this case, it is possible for a considerable amount of pollutants to deposit in the star’s vast radiative envelope below the convective layer. For a swarm of planetesimals falling onto the star, we assume a size distribution of $dN/da \sim a^{-3.5}$ (Wetherill & Stewart 1989) with 1 $R_\odot$ as the largest size of the planetesimals. This mass distribution is comparable to those inferred for the asteroids and the Kuiper belt objects, and for the impactors of lunar craters (Hartmann 1999). We assume that the residual planetesimals and embryos plunge radially toward the center of the host star. Based on the results of previous simulations of meteoritic impacts on the atmosphere of Venus (Korycansky & Zahnle 2005), we assume that the amount of ablated mass of individual planetesimals is comparable to the mass of the background gas encountered along the path. Thus, the disruption depth of planetesimals is a function of their sizes.

Given the density distribution of a particular stellar structure, we can integrate to obtain the deposited mass at each layer as a function of the penetrating depth. Figure 1 shows the mass distribution of 10 $M_\odot$ pollutants deposited along the stellar radius for a 1.3 $M_\odot$ star of an initial solar metallicity at ZAMS. The convective and radiative zones are marked and separated by a vertical dotted line.
With little knowledge of the time when pollution may happen, we choose the ZAMS as the beginning time of the heavy-element accretion. In the pre–main sequence, the stellar surface convective zone is so large that the accretion of heavy elements cannot cause any significant surface metallicity enhancement (Ford et al. 1999). When the stellar evolution is approaching the ZAMS, i.e., 10 Myr before the ZAMS, the convective zone retreats rapidly to the surface and its size becomes comparable to the size of the main-sequence star’s convective zone. The enrichment of surface heavy elements due to pollution becomes nonnegligible and detectable. From then on and during the main sequence, the size of the surface convective zone does not change much. Thus, the polluted models would not be very sensitive to the exact time of heavy-element accretion. The only difference is that the star which accretes heavy elements in the early evolutionary stage will have a slightly lower surface metallicity than the one which is polluted by the same amount of heavy elements in the late stage, because the surface metallicity enhancement due to accretion will be reduced after a long time of heavy-element diffusion. For numerical stability, we assume that the accretion may last for a duration of 100 Myr. Observations in the mid-IR have shown that the total mass of the grains in the disk declines with time (Rieke et al. 2005). We have thus assumed a time dependence of the rate of planetesimal bombardment suggested by the IR observations. The accretion rate thus declines monotonically as the star evolves.

3. THE EFFECT OF POLLUTION ON THE STELLAR STRUCTURE

For the first limiting case of the accreted planetesimals’ trajectory, we mix all the heavy elements of the accreted material through the convective zone. In the second case, we still uniformly mixed those materials which were ablated in the convective region, while for the relatively large planetesimals penetrating below the convective layer, we added the heavy elements deposited in these regions to the local metallicity distribution in the radiative region. Without a better understanding of the accreted material’s composition, we assume that it contains no hydrogen or helium but has the same composition of heavy elements as that of the star in our calculation. The helium abundance of the host star was deduced using \( \delta Y/\delta Z = (Y - Y_\odot)/(Z - Z_\odot) = 2.5 \) (Pagel et al. 1992).

In Figure 2a we show a comparison between the two limiting pollution prescriptions of the initial metallicity profiles in the outer region of our polluted stellar model. In each case, we assume \( \sim 5 M_\odot \) debris rocky material is accreted onto a ZAMS host star. From Figures 1 and 2a, we find that a considerable amount of the accreted material enters the radiative region in the case where the planetesimals collide with the host star in a head-on trajectory. In the following 1 million years, another \( 5 M_\odot \) of rocky material is added. Figure 2b shows the metallicity profiles of the two models at the time of \( 1 \times 10^8 \) yr, when all \( 10 M_\odot \) heavy elemental material has been accreted. At that time, some diffusion has already occurred for both models at the boundary between the convective and radiative regions. Figure 2c shows the metallicity profiles for both models at the time of \( 3 \times 10^9 \) yr, which is approximately the age of HD 149026. Due to the diffusion of heavy elements and the deepening of the surface convective zone, the surface metallicity at this late epoch has decreased considerably in both models.

Figure 3 shows the evolutionary tracks by adding the accreted material in the two limiting ways. Both models have a mass of \( 1.3 M_\odot \) and an initial solar metallicity. We can find that during the main sequence, especially where the tracks locate within the observational error bars for HD 149026, there is little difference between the two models in luminosity and effective temperature. However, while the model with significant amounts of material deposited in the radiative zone can produce a surface metallicity within the observed uncertainties for [Fe/H] of HD 149026, the model with all material mixed in the convective zone has a surface metallicity much larger than the upper limit of the observed [Fe/H]. Therefore, the main effect of the metallicity enhancement in the radiative zone compared with that in the convection zone is that it can increase the radiative opacity, reddening
the star, and make it expand without causing significant surface metallicity increase. As HD 149026 has a very shallow surface convective zone, it is more likely that a lot of infalling planetesimals will penetrate into the radiative region. Therefore, we use the second pollution prescription for the following calculations.

4. EVOLUTION OF HD 149026

Based on the above definitions of pollution, we construct polluted stellar models for HD 149026, which hosts a Saturn-mass planet with a large dense core in a 2.8766 day orbit (Sato et al. 2005). Three basic observational parameters are required to constrain our models. From spectroscopic analysis (Sato et al. 2005), the effective temperature $T_{\text{eff}}$ and metallicity $[\text{Fe/H}]$ for HD 149026 are determined to be 6147 ± 50 K and 0.36 ± 0.05, respectively. Another important parameter is its luminosity. From the Hipparcos catalog (ESA 1997), the parallax and visual magnitude of HD 149026 are 12.68 ± 0.79 mas and 8.15, respectively. The bolometric correction (BC) is estimated to be $-0.026 ± 0.006$ by interpolating the effective temperature using the $T_{\text{eff}}$-BC conversion relationship provided by Flower (1996). Then, we arrived at a bolometric luminosity of $2.756^{+0.363}_{-0.300} L_\odot$ with a 1 σ error bar of the parallax. We show below the results of a range of theoretical models with different stellar parameter (such as stellar mass and interior metallicity) that are within the observational uncertainties. For example, a 3 σ uncertainty in the parallax distance determination leads to an uncertainty of $(+1.393, -0.789)L_\odot$ in the absolute luminosity of HD 149026.

For the standard model of HD 149026 without pollution (with a homogeneous metallicity distribution), we obtain a stellar mass of 1.3 $M_\odot$ and an age of 2.27 Gyr as the best fit of the observational data. This is consistent with the calculations of this star in Sato et al. (2005) within the uncertainty. From this model, we attribute this star to a post-main-sequence star. It is also supported by the ages of the best-fit polluted models, which will be presented below. Note that we cannot completely exclude the possibility that this star is still on the main sequence or a giant just from stellar models, considering the large error range in the present observational data. No age from chromospheric activity has been yielded for this star because no CaH and K line emission was observed. Therefore, we expect the evolutionary stage of this star to be confirmed by improved parallax and effective temperature determinations.

We first illustrate the effect of pollution of the stellar evolution track in the color-magnitude diagram. In Figure 4 we show a series of models with $M_*=1.3 M_\odot$ and $Z=1.5 Z_\odot$ throughout the star. In this figure, the evolutionary track of a model with an unpolluted homogeneous interior (with 1.5 solar metallicity) is denoted by a thin solid line. Overplotted are the evolutionary tracks of models, which are polluted by a total amount 10, 30, 50, and 70 $M_\odot$ of heavy elements. Two ages are labeled on the tracks. For comparison, we have also plotted the evolutionary track of a 1.3 $M_\odot$ model with the observed metallicity of HD 149026 (the thick solid line in Fig. 4).

Contrasting these models at any given effective temperature, we find that the accretion of heavy elements decreases the luminosity as a consequence of the opacity enhancement in the radiative layer. The reduced efficiency of radiation transfer also increases the central temperature of the star and speeds up the stellar evolution process. Consequently, at the same age, the surface metallicity enhancement has the general effects of (1) reducing the effective temperature, (2) increasing the stellar radius, and (3) decreasing the luminosity.

5. OBSERVATIONAL TESTS

In this section, we show that a star’s evolution track is mostly determined by its mass and internal metallicity. Therefore, we can extrapolate the magnitude of a star’s internal metallicity from the observable quantities: its mass, luminosity, and effective temperature. For HD 149026, the difference between this inferred internal metallicity and its observed surface metallicity ($[\text{Fe/H}]=0.36$) provides a quantitative determination on the extent of heavy-element pollution in this star.

5.1. Evolution Tracks for a Possible Range of Pollution Models

We carry out below a systematic quantitative analysis to accomplish the above stated goal. In order to place constraints on model parameters, we adopt three sets, 0.5, 1, and 1.5 times the solar value, for the internal metallicity of the star. For each set, we first constructed a series of homogeneous stellar evolution models. From their tracks on the color-magnitude diagram, we
isolate the range of stellar masses which are allowed by the observational constraints.

We then iterate these models to include the effect of pollution. In order to match the observed surface metallicity [Fe/H], we assume different amounts of heavy-element accretion. The accretion of heavy elements only increases the metallicity of the surface layer, while that in the deep stellar interior retains its initial value. In the accretion prescription, diffusion is taken into account even though this effect is negligible. With these modifications, we reevaluate the range of observationally compatible stellar mass for each set of internal metallicity.

In Figure 5 we consider a series of models (with different \( M_* \)) with initial solar metallicity which is also preserved in the stellar interior. We plot three sets of polluted models with different stellar masses in dashed lines. For each mass, the two tracks correspond to the upper and lower limit of metal required to match the observed range in [Fe/H], These nearly overlapping tracks indicate that the values of \( L_* \) and \( T_{\text{eff}} \) are more sensitive to \( M_* \) than to the exact value of [Fe/H].

Overplotted in Figure 5 is the 1 \( \sigma \) (solid lines) error box for the observed effective temperature and luminosity. In view of the large uncertainties in the best available astrometric data, we also illustrate the extent of the error box (dotted lines) introduced by a 3 \( \sigma \) deviation in the parallax distance determination. Models with \( M_* > 1.35 \, M_{\odot} \) are excluded because they produce over-luminous (for the observed range of \( T_{\text{eff}} \)) tracks. Models with \( M_* < 1.15 \, M_{\odot} \) are excluded because they produce insufficiently hot \( T_{\text{eff}} \) (for the observed range of \( L_* \)) tracks. A star of \( M_* = 1.223 \, M_{\odot} \) passes the center of the error bar box. For this particular model, the total amount of pollutant required to bring the surface metallicity to the observed value is \( \Delta M_Z \simeq 25 \, M_{\odot} \), which is a significant fraction of the heavy-element content in HD 149026b. The stellar age which satisfies the best observational data (shown as the small circle in the center of the error bar box) is 3.18 Gyr.

We considered another two series of models with initial metallicity equal to 0.5 and 1.5 times that of the Sun (Figs. 6 and 7). Obviously, more heavy elements are needed to match the observed [Fe/H] for the \( Z_{\text{internal}} = 0.5 \, Z_{\odot} \) models, and less heavy elements are needed for the \( Z_{\text{internal}} = 1.5 \, Z_{\odot} \) case compared to the models with internal solar metallicity in Figure 5. For the low-metallicity case, models with \( M_* < 1.05 \, M_{\odot} \) and \( M_* > 1.2 \, M_{\odot} \) are excluded by the observational error box. We obtain the best-fit model with \( M_* = 1.109 \, M_{\odot} \), which accretes a total amount of heavy elements of \( \Delta M_Z \simeq 31 \, M_{\odot} \). The track of this best-fit model passes through the center of the error box at the age of 4.67 Gyr, while for the high-metallicity case, models with \( 1.2 \, M_{\odot} < M_* < 1.4 \, M_{\odot} \) pass through the extended error box with \( M_* = 1.273 \, M_{\odot} \) as a best fit, which requires a total amount of pollutant of \( \Delta M_Z \simeq 10 \, M_{\odot} \). The stellar age is estimated to be 2.65 Gyr for this case. Note that the unpolluted model in Figure 4 which matches the most probable observational data has \( M_* = 1.3 \, M_{\odot} \).

From the above results of HD 149026, we find that the stellar mass and the internal metallicity are degenerate parameters in determining its location on the H-R diagram, even if other observational parameters are very well constrained. To illustrate this degeneracy, we plot in Figure 8 the four best-fit models together, including the unpolluted model and three polluted models with different sets of mass and internal metallicities. We find that all the tracks pass through the center of the error box, and all the models have almost the same surface metallicity as observed. It is impossible to distinguish between polluted and unpolluted models just by using present observational constraints, such as luminosity, effective temperature, and surface.
metallicity. In traditional stellar modeling, the stellar mass is evaluated from isochrone fitting under the assumption of chemical homogeneity (cf. Sato et al. 2005). Our approach is to abandon this assumption and infer the star’s internal metallicity from an observationally determined stellar mass (see §5.3 below). A definite difference between the inferred internal metallicity and the surface value is good evidence of the occurrence of pollution onto the star.

5.2. Main Sources of Uncertainties

In principle, the amount of heavy-element pollution can be uniquely estimated with high-precision determinations of the stellar mass, luminosity, effective temperature, and surface metallicity. However, the large uncertainties in the best, presently available data do not place any stringent constraints on the stellar models. We cannot yet infer with any degree of confidence, whether pollution has occurred.

The effective temperature and surface metallicity have been determined quite well by present spectroscopic observations. The stellar luminosity adopted in our models is calculated using the parallax and visual magnitude obtained from the Hipparcos catalog (ESA 1997). For HD 149026 with a visual magnitude of 8.15, the uncertainty of parallax is ±0.79 mas, which implies an ∼10% in the stellar luminosity (see §4). Higher accuracy is anticipated for the European Gaia astrometry mission, which is due for launch in 2011. For stars with \( V = 10 \), the parallax accuracy is expected to be around 7 μas, which is less than 1% of the present observational uncertainty (Jordi et al. 2006). This improvement reduces the uncertainty in luminosity by a factor of 30. In this case, the degeneracy of stellar models induced by the uncertainty in luminosity would be largely relieved.

The stellar mass is then the key parameter whose accuracy we mainly rely on to distinguish between polluted and unpolluted models. Our model results show that the inferred internal metallicity is an increasing function of the stellar mass (see Figs. 5–8). If the independently measured stellar mass, even taking into account the observational uncertainties, is smaller than the one obtained from unpolluted stellar models, our models would suggest that it is a sign of heavy-element pollution, because the internal metallicity inferred from our model would be lower than the surface value, which is also the bulk metallicity of the chemical homogeneous model. Therefore, the expected precision of stellar mass depends on the central value of stellar mass obtained from the observation. Take the above models of HD 149026, for example: supposing the central value of stellar mass is determined to be 1.11 \( M_\odot \), an error within 17% in the mass measurement would be sufficient to test our models. If the central value of \( M_\star \) is 1.27 \( M_\odot \), we would need the error to be less than 2.4%. The above estimations about the accuracy of stellar mass required are under the optimal cases that there is no systematic error in the stellar modeling. The most important uncertainty that affects the stellar models is the initial helium abundance. Without any observational data for this parameter, we assume the ratio \( \delta Y/\delta Z = (Y - Y_\odot)/(Z - Z_\odot) \) to be 2.5, based on the studies of chemical evolution of the Galaxy (Pagel et al. 1992). We have tested the influence of this ratio on the mass determination of stellar modeling. We find that, varying this ratio by 1, the stellar mass would be changed by 1% in order to fit the same luminosity and temperature in the H-R diagram. The treatment of convection is another uncertainty in the stellar models. Varying the convective parameter in our model by 20% would produce a less than 1% uncertainty in the stellar mass to fit the observations. Moreover, the effect caused by this uncertainty has been minimized by choosing the mixing-length parameter through solar model calibration.

5.3. Some Potential Methods of Accurate Stellar Mass Determination

Presently, precise measurements of stellar mass remain technically challenging. Usually, stellar mass can be determined in binary systems using astrometric methods. For eclipsing binaries, an accuracy of 2%–3% can be achieved in the best case (Balega et al. 2007). There is no known stellar companion to HD 149026. However, its planetary companion undergoes stellar transit. In such systems, it is possible to determine the star’s average density by solving the equations of transit geometry and Kepler’s third law. Since the stellar radius can be determined independently with the Stefan-Boltzmann law (Sato et al. 2005), the stellar mass can then be obtained.

The average stellar density can be derived as

\[
\rho_* = \frac{32P}{\pi G} \left( \frac{\Delta F^{3/4}}{(t_f - t_0)^{3/2}} \right),
\]

where \( t_f \) is the total transit duration, \( t_p \) is the duration of the transit completely inside ingress and egress, \( P \) is the period, and \( \Delta F \) is the transit depth (Seager & Mallén-Ornelas 2003; Gillon et al. 2006; Winn 2008). This calculation provides the stellar mean density directly from the observations of transit light curve. When using Kepler’s third law, \( M_p \ll M_\star \) and circular orbit for the transit planet are assumed. Although finite eccentricity can introduce modifications in the transit duration (Burke 2008; Ford et al. 2008), this effect can be easily taken into account. Nevertheless, highly precise radial velocity measurements are needed to determine the planet’s eccentricity (to within \( \sim 10^{-2} \)) and longitude of the nodes so that our method can be fully utilized to determine the extent of stellar pollution.

The determined values of the stellar density depend on the transit shape of the light curve \( (t_f/t_r) \) and the ratio of planet and star sizes \( (\Delta F)^{1/2} \), which introduce observational uncertainties (Seager & Mallén-Ornelas 2003). The measurement of the mean density is further complicated when the limb-darkening effect is taken into account, because the transit geometry is largely affected by this phenomenon (see Seager & Mallén-Ornelas [2003] for more details).

For HD 149026b, Winn (2008) calculates its transit parameters by analyzing five new transits and also previous transit data.
He obtains a mean stellar density for HD 149026 of around 0.528 $M_\odot/R_\odot^3$ with an uncertainty up to ~30%. He then assumes a stellar mass of 1.3 ± 0.06 $M_\odot$ (based on the isochrone fitting by Sato et al. (2005)) to obtain a stellar radius of 1.35$^{+0.17}_{-0.02}$ $R_\odot$. He suggests that this value is, within 1 $\sigma$ uncertainty, from that obtained from the Stefan-Boltzmann law (1.45 ± 0.1 $R_\odot$). Here we adopt the stellar radius determined by the Stefan-Boltzmann law at its face value, and use the star’s average density inferred from the transit equations to determine the mass of HD 149026 to be 1.61$^{+0.23}_{-0.56}$ $M_\odot$. The large uncertainties in this value prevent any meaningful constraints on the internal metallicity of this star.

In principle, the quality of the transit light curve can be greatly improved in this system with high-precision photometry. In another transiting system, Pont et al. (2007) have already obtained an accuracy of 3% for the stellar density of HD 189733 with Hubble Space Telescope observation. Meanwhile, the stellar radius can be constrained much better by the improved luminosity measurements. Considering that the error in luminosity will be scaled down by 30% due to accurate measurement of parallax, the uncertainty in stellar radius determination would be reduced to 1.8%. Thus, it is possible that the stellar mass can be obtained with accuracy at least for some cases, as required to test our theoretical models.

For some planetary systems, gravitational microlensing is another promising method to determine the stellar mass of single stars. When a nearby star moves in front of a distant background star, it causes light deflection and induces gravitational microlensing effects. By measuring the geometry of the microlensing effect, the mass of the lens star can be derived from solving a set of lens equations (Paczynski 1996; Miralda-Escude 1996). In order to observe the objects over a reasonable period of the time, nearby stars with high proper motion are required for this measurement. The stellar mass of an M dwarf has been determined using this method with an uncertainty of 17% (Gould et al. 2004). This error can be largely decreased by better determination of distance and better photometry of the source. Paczynski (1998) has proposed that it is possible to measure $M_\star$ of nearby stars with an accuracy of 1% using this method using the Space Interferometry Mission (SIM). With the aforementioned upcoming high-precision astrometry missions, we expect that our theoretical stellar models will be able to test whether pollution is a significant effect inducing the high metallicities of stars with planets.

Another direct probe for testing the occurrence of pollution is associated with the modification in the internal structures and the oscillation frequencies of the stars. We will consider elsewhere the difference in the $g$-mode oscillation frequency associated with the dispersion in the structure of the models.

6. SUMMARY AND DISCUSSIONS

In this paper, we considered the possibility that the outer envelope of a metal-rich planet-bearing star HD 149026 may have been significantly polluted by residual planetesimals or some gas giant planets. This system is particularly interesting because it contains a planet with most of its mass in its core and an intermediate-mass star which has recently entered the post-main-sequence evolutionary phase. In a subsequent paper, we will suggest that this large core Saturn-mass planet HD 149026b was formed through giant impacts onto a proto–gas giant planet by either residual protoplanetary embryos or by other gas giant planets in the proximity of the host star. A significant fraction of metal of the building blocks may not merge or be retained as a consequence of grazing high-velocity collisions. However, those debris may undergo orbital decay or remain in the close proximity of HD 149026b’s present-day orbit.

We assume that a substantial fraction of the original residual planetesimals in the neighborhood of HD 149026b may have been scattered into its host star, which is an F star with a very shallow convective layer. We carried out evolution calculations to take into account the effect of stellar pollution. We suggest that in this and other F stars with planets, the extent of stellar pollution by residual planetesimals may be tested by accurate determinations of their mass, luminosity, and effective temperature. Such accurate measurements, when combined with an accurate transit light curve, may provide a firm support on the stellar accretion of a substantial population of terrestrial-planet-building material as well as one or more gas giant planets similar to HD 149026b.

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