THE ASTROPHYSICAL JOURNAL, 347:910–914, 1989 December 15

THE NEBULA AROUND EGB 6/PG 0950+139: EVIDENCE FOR ABLATION OF A JOVIAN PLANET?

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Received 1989 March 3; accepted 1989 May 23

ABSTRACT

EGB 6 is a very large planetary nebula whose central star, 0950+139, is a hot DA/DAO white dwarf, which is associated with a very compact and dense emission nebulosity (Liebert *et al.*).

We have derived the parameters of this nebula from a photoionization model, and show it to have solar-like abundances, to have a radius of 5×10^{14} cm (30 AU), and to be characterized by a mean hydrogen particle density of 2.2×10^6 cm^{-3}, and a filling factor of order $\log \epsilon \sim -3.4$. We discuss the origin of this extraordinary nebula, and show that its properties are consistent with the photoionization-driven ablation of a low-density planet or planetary accretion disk at a distance of some 2–4 AU from the central star.

Subject headings: nebulae: individual (EGB 6/PG 0950+139) — nebulae: planetary

I. INTRODUCTION

The search for planets around stars (other than our Sun) has been a particular interest to astronomers and, indeed, the public at large. However, this difficult effort has enjoyed only indifferent success to date. With new infrared detectors, for example, companions to nearby stars have masses near or possibly below the mass limit for hydrogen burning (~ 0.08 $M_\odot$) have been detected in their own radiation. Recently, Zuckerman and Becklin (1987) and Becklin and Zuckerman (1988) have searched for such objects as companions to white dwarf stars, with two noteworthy successes. In this paper we make the case (in the system EGB 6/PG 0950+139) for the existence of a truly planetary companion rendered detectable by the photoionization ablation driven by its very hot white dwarf primary star.

The system EGB 6/PG 0950+139 is a very hot DA white dwarf juxtaposed with a most unusual nebula. It was first discovered as an extended, possible planetary nebula of very low surface brightness by Ellis, Grayson, and Bond (1984). The central star was independently detected in the Palomar Green Survey and found to be a very hot DA white dwarf (Fleming, Liebert, and Green 1986). Both groups of authors also found a bright, unresolved "core" component to the nebula, unresolved at the derived distance of 460 pc, which has highly unusual properties for it to be associated with a star with a postasymptotic giant branch age of several times 10^5 yr (Liebert 1989; Liebert *et al.* 1989). The inner nebula was found to be extremely dense ($n_e \geq 10^6$ cm^{-3}) and is ionization bounded at an apparent scale of order 10 AU. Moreover, the nebular gas was found to be moving no faster than 50 km s^{-1}. In the simplified analysis, however, the electron temperature and density was estimated only crudely, and the filling factor was completely undetermined.

In this paper, a photoionization model is calculated and more accurate nebular parameters and abundances are derived. In § III, we develop a model quite different from those discussed by Liebert *et al.* (1989), in which a bloated, Jovian planet, or the material captured by this planet during the asymptotic giant branch phase of evolution, is presumed to be the source of the material photoionized by the white dwarf. The released material is confined by the stellar wind to a thin, dense torus and is slowly expelled from the system. The general implications of this scenario for evolved stars having Jovian planets are considered in § V.

II. A PHOTOIONIZATION MODEL

In order to improve on the results of Liebert *et al.* (1989), and to provide additional observational constraints on the properties of the nebula, we have constructed spherical, constant density, photoionization models using the general-purpose modeling code MAPPINGS (Binette, Dopita, and Tuohy 1985). It is safe to assume that the nebula is in photoionization equilibrium, even in the case that it expands and dissipates within a year, because the very high density, $n_{\rm H} \geq 10^6$ cm^{-3}, ensures that the recombination time scale, $\tau_{\rm rec} \sim \{2.10^5/n_{\rm H}\}$ yr, is always much shorter than any dynamical time scale.

We assume that the central star emits a blackbody distribution, and we initially adopted the stellar parameters as given in Liebert *et al.* (1989), $T_{\rm eff} = 70{,}000$ K; $R/R_\odot = 0.022$. However, we found that the ratio of the helium lines, and the excitation generally, was better fitted by $T_{\rm eff} = 72{,}000$ K; $R/R_\odot = 0.021$. These parameters are still very close to those derived by Liebert *et al.* by modeling the hydrogen line profiles of the central star.

The [O III] λ4363/(4959 + 5007) Å ratio is very sensitive to both the temperature, and, as a result of collisional deexcitation at these high densities, to the density as well. However, the temperature is well determined in equilibrium photoionization models, provided the abundances are known. Thus, the density can be explicitly determined from the models. We assumed a solar abundance set, and then iterated on the density until we fitted the [O III] ratio. This procedure yielded a mean hydrogen particle density, $n_{\rm H} = 2.2(\pm 0.2) \times 10^6$ cm^{-3}, and a mean electron density on the O^{++} zone of 2.52×10^6 cm^{-3}. This can be compared with the value obtained by Liebert *et al.* 1988; $n_e \sim 2.7 \times 10^6$ cm^{-3}. The mean electron temperature in the O^{++} zone is 11,400 K.

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TABLE 1

A PHOTOIONIZATION MODEL FOR THE COMPACT NEBULA ASSOCIATED WITH EGB 6

Ion	Line Flux WRT Observed	$H\beta = 100.0$ Model
[O II] $\lambda3728$	<18	1.4
[Ne III] $\lambda3869$	134	119
[S II] $\lambda4068, 76$	<13	3.1
$H\delta$ $\lambda4101$	25	26
$H\gamma$ $\lambda4340$	47	47
[O III] $\lambda4363$	56	55
He II $\lambda4686$	7:	7.2
[Ar IV] $\lambda4711$	19	0.5
He I $\lambda4713$	...	...
[Ar IV] $\lambda4740$	7	3.6
$H\beta$ $\lambda4861$	100	100
[O III] $\lambda4959$	172	181
[O III] $\lambda5007$	550	522
He I $\lambda5876$	16	17
[O I] $\lambda6300$	20	3.5
[S III] $\lambda6310$	...	11
[N II] $\lambda6548$	...	1.0
$H\alpha$ $\lambda6563$	267	278
[N II] $\lambda6584$	...	3.1
He I $\lambda6678$	7	4.9
[Ar III] $\lambda7165$	...	9.9
[O II] $\lambda7318, 30$	12	37
[S III] $\lambda9069$	...	15
$\log (L_{H\beta})$ (erg s^{-1})	29.23	32.67

B. PARAMETERS FOR PHOTOIONIZATION MODEL

Model Parameters	Value
T_{eff}	72,000
$R/R_\odot$	0.22
n_H (cm^{-3})	2.2×10^6
R_{neb} (cm)	5.7×10^{14}
N(He)/N(H)	0.14
$Z/Z_\odot$	1.0

We found that the best reproduction of the absolute He line strengths was obtained with a slight helium overabundance, $N(\text{He})/N(\text{H}) = 0.14$. However, it was not necessary to iterate on the abundance set of the heavier elements at all. The "solar" abundance set was, by number with respect to hydrogen, C:N:O:Ne:Mg:Si:S:Cl:Ar = 4.2×10^{-4}:8.7×10^{-5}:6.9×10^{-4}:9.8×10^{-5}:4.0×10^{-5}:3.8×10^{-5}:1.9×10^{-5}:1.8×10^{-7}:4.0×10^{-6}. An excellent fit with the observed spectrum was obtained with these parameters, as can be seen in Table 1. This model is not influenced by the abundances of the elements heavier than argon, since these are unimportant as coolants.

Note that the absolute $H\beta$ flux calculated for this model is very much larger than what is observed. This implies that the ionized material occupied only a very small fraction of the spherical volume. Comparison of these figures implies a filling factor of only $\log \epsilon \sim -3.44$. Since the radius of the Strömgren sphere is 5.7×10^{14} cm (38 AU), the ionized mass is only $7 \times 10^{-10} M_\odot$.

III. THE ORIGIN OF THE NEBULAR GAS

In Liebert *et al.* (1989), three possible origins of the nebular gas were considered. First, the gas had been recently ejected in a discrete nova-like event. Second, the material is being continuously ejected from the white dwarf in a steady wind. Third, the material is being boiled off in some way from a close, invisible dwarf companion. The first of these has the problem that there is no evidence that there has been any recent variability, either in the star or in the nebula. The second possibility is rendered unlikely by the observation that the expansion velocity in the ionized gas is orders of magnitudes less than the escape velocity of the host star. The third hypothesis is not supported by any evidence for the existence of a close companion star.

If we assume that the nebula is the result of photoionization of a stellar wind from an M dwarf companion, the typical mass loss rates, $\dot{M} \sim 10^{-13}$–10^{-12} $M_\odot$ yr^{-1} (Coleman and Worden 1976), are near the required ablation rate. However, the wind velocities (typically $\geq 10^3$ km s^{-1}) are two orders of magnitude too high to be consistent with the velocity broadening in this nebula.

Two other possibilities are that the cloud represents a remnant of the cool wind ejected during the asymptotic giant ejection phase, or material that has been accreted to the system in a chance encounter with a dense cloud. However, the stellar wind in the planetary nebula phase would have been very effective in stripping out any matter from the region of the star, the density of the red giant wind would be too low to be consistent with the observed density of the nebula, and both these hypotheses are inconsistent with the very low filling factor we observe.

In this section, we would like to develop a more promising scenario, namely, that the nebula is the result of photoionization-driven ablation of the outer layers of a Jovian planet or of a gaseous disk about a Jovian planet. In essence, this idea supposes that the central star can photoionize and heat the outermost layer of the planetary atmosphere or gaseous disk about the planet. Provided that the planetary velocity of escape is lower than, or comparable with, the mean thermal velocity of the ionized plasma, this material will be driven away from the planet, and will form a plasma torus. The satellite body or disk has to have a solar-like composition, at least as far as the CNO group of elements are concerned, and also as far as the noble gases are concerned. This assumption appears to be well justified for the Jovian planets. Jupiter, for example, exhibits "normal" atmospheric abundances within the limitations of interpretation of the atmospheric chemistry and the mixing ratios (Prin and Owen 1976).

We will show that such an origin of the ionized gas serves at once to explain the apparent steady-state nature of the nebula, the low expansion velocity, and the small filling factor inferred in the previous section.

a) Planetary Ablation

Suppose that a Jovian-like planet of radius r is in orbit at a distance R from the central star, which is producing N_* ionizing photons per second. Then, providing that the outer layers of the atmosphere are exposed to the full brunt of the radiation field of the central star, then they will be ablated at a rate $\dot{M}$ gm · s^{-1}, where

$$(1/\mu m_H)\dot{M} = 0.25\eta N_*(r/R)^2 \tag{3.1}$$

the factor η being an efficiency parameter, of order of, or less than, unity. For stars with parameters close to what we observe, the ionizing flux can be written in terms of the luminosity, $N_* = 9 \times 10^{44}$ $(L_*/10\ L_\odot)$. If R_1 is the distance of the body in units of AU, and $r_{0.1}$ is the radius of the ablating body in units of 0.1 $R_\odot$, then

$$\dot{M} = 1.1 \times 10^{14}\eta(L_*/10\ L_\odot)(r_{0.1}/R_1)^2 \text{ g s}^{-1} \ . \quad (3.2)$$

The distance of the planet would have to have been greater than ~2 AU to ensure that it was not swallowed up by the central star as it passed through the asymptotic giant branch (AGB) phase of its evolution, as considered in detail by Livio and Soker (1984).

For equation (3.2) to be rigorously true, the escape velocity would have to be comparable to, or less than, the thermal velocity of the ionized gas at a temperature of 11,400 K, 14.7 km s^{-1}. Jupiter has, in fact, an escape velocity of 67 km s^{-1}, and Saturn an escape velocity of 37 km s^{-1}. These figures suggest that the ionized gas may build up in the vicinity of a Jovian-like planetary body to the point where recombinations become important. In this case, ablation is driven by the pressure gradient in the ionized flow, which can easily overcome the gravity of the planet. In this case, we can equate the number of ionizing photons falling on unit area with the number of ionizations occurring in a column of unit area plus the number of new ionizations occurring at the ionization front. The equation of photoionization equilibrium now reads

$$N_*/4\pi R^2 = \beta n_{\text{II}}^2 r_{\text{eff}}/5 + v_{\text{ion}} n_{\text{I}} \quad (3.3)$$

where the radius and velocity of the ionization front are r_{eff}, v_{ion}, respectively, the density in the ionized material directly behind the ionization front is n_{II}, and the density in the unionized material just ahead of the ionization front is n_{I}. In equation (3.3) we have assumed that the ionized flow is in photoionization equilibrium against the recombinations occurring within it, and that it is of constant velocity with $n(r) = n_{\text{II}}(r/r_{\text{eff}})^{-2}$. The ionization front is in fact stationary in the flow, and therefore must be D-critical, with $v_{\text{ion}} = (2kT_{\text{I}}/\mu m_{\text{H}})^{1/2}$. The ionization front is supplied with gas moving on ballistic trajectories from the critical layer of the atmosphere. At this layer, the particle density, n_c, becomes so low that the mean free path, λ, becomes comparable with the barometric scale height H. This condition yields

$$H = (kT_{\text{I}} r_c^2/\mu \text{m}_{\text{H}} GM_p) = \lambda = (\sigma n_c)^{-1} \ . \quad (3.4)$$

The radiative equilibrium temperature of these atmosphere layers is ~500 K, so that, for a molecular hydrogen atmosphere, the scale height is $H \sim 130\ (T_{500} r_{0.1}{}^2 M_{30}{}^{-1})$ km, where the temperature is measured in units of 500 K, and the planetary mass in units of 10^{30} gm. The critical density is therefore $n_c \sim 8 \times 10^8\ (T_{500}{}^{-1}\ r_{0.1}{}^{-2}\ M_{30})$ cm^{-3}. The mass flux through the ionization front is simply the mass flux through the critical layer multiplied by the fraction of atoms with energies sufficient to carry them up to the radius of the ionization front. Thus,

$$\dot{M} = 2\pi r_c^2(2kT_{\text{I}}\ \mu \text{m}_{\text{H}})^{1/2} n_c \times \exp\left[-(\mu \text{m}_{\text{H}} GM_p/2kT_{\text{I}})(r_c^{-1} - r_{\text{eff}}^{-1})\right] \quad (3.5)$$

In practice, the effective radius of the planet for photoionization, r_{eff}, cannot be much larger than the effective radius of the atmosphere, r_c, since otherwise the particle density would fall too low to be reconciled with observation. Thus, the exponential term is of order unity, and,

$$\dot{M} = 2 \times 10^{11}(T_{500}{}^{-1/2} M_{30}) \text{ g s}^{-1} \ . \quad (3.6)$$

Equations (3.2) and (3.6) are, respectively, upper and lower limits on the ablation rate. Equation (3.2) implies that an amount of matter equal to the total of the ionized material, $7 \times 10^{-10}\ M_\odot$, could be driven off in a time scale of $\sim 400(R_1/r_{0.1})^2$ yr, whereas equation (3.6) would require a time scale of $\sim 2.10^5\ (T_{500}{}^{1/2} M_{30}{}^{-1})$ yr. In the steady state, this should equal the dissipation time scale of the nebula. These are uncomfortably long compared with the dynamical time scale estimated from the width of the emission lines, in the range of 1–10 yr. However, the dynamical age of the nebula cannot be simply estimated from this quantity, since a substantial component of this may be due to Keplerian motion. The thermal velocity of the plasma (~10 km s^{-1}) is probably less than the orbital velocity, ($\sim 22R_1{}^{1/2}$ km s^{-1}), so the plasma will form a closed torus around the orbit of the source body.

The total mass fraction lost by a planet will be small, even taking into account the rapid ablation caused by the high luminosity during the planetary nebula phase of evolution. Equation (3.2) shows that the lifetime of a planet of mass 10^{30} g is some 6×10^5 yr, even at the maximum luminosity in the planetary nebula phase. Today, the ablation time scale is hundreds of times the lifetime of the star in its hot phase. Thus, at worst, only a few percent of the total mass will be lost.

An alternative possibility is that the material is stripped off directly by the action of the stellar wind on the upper atmosphere. The stellar wind will form a stand-off shock, and the very high temperature shocked stellar wind could turbulently mix with the atmospheric gases to form a mass-loaded stream from the planet. In this case, setting the momentum fluxes equal

$$V_w \dot{M} = 0.25(L/c) \cdot (r/R)^2 \ , \quad (3.7)$$

where V_w is the velocity of the mass-loaded wind, ~10 km s^{-1}. Substituting numbers gives

$$\dot{M} = 7.2 \times 10^{10}(L_*/10\ L_\odot) \cdot (r_{0.1}/R_1)^2 \text{ gm s}^{-1} \quad (3.8)$$

Thus, direct stellar wind stripping of the atmosphere is orders of magnitude less effective than photoionization stripping.

b) A Cometary Origin

In the case of a cometary origin of the ionized plasma, the outgassing is driven by direct outgassing of the nucleus, and, for gas-rich comets such as Bradfield (1979X), is observed to vary as a steep power law of the heliocentric distance $\sim r^{-3.5}$ (Weaver *et al.* 1981). In this case, photoionization will not be important until a long way out in the flow, where an equation such as (3.3) will apply. In order to resupply the ionized plasma within a dynamical time, τ_{dyn}, a flow of $\sim 5 \times 10^{14}(\tau_{\text{dyn}}/100 \text{ yr})$ g s^{-1} is required. This is some 10^6 times higher than would be expected from a "normal" comet, and possibly some 10^{2-3} times greater than for a "great" comet. Furthermore, the composition of comets is very deficient in hydrogen, since the object is mainly composed of ices. A cometary origin for the plasma therefore seems unlikely.

IV. THE PLASMA TORUS

The main effect of the stellar wind will be to help confine the ionized plasma to a thin torus. Equating the gas pressure, P, to the effective ram pressure in the stellar wind yields:

$$P = 3n_{\text{H}} kT = \beta(\gamma L/c)(1/4\pi R^2) \ . \quad (4.1)$$

The factor β is the ratio of the stagnation pressure in the ionized gas to the ram pressure in the stellar wind. It is in the range of 2–4, γ is the ratio of momentum in the stellar wind to that of the radiation field, and should be in the range of 0.5–3.

The observed gas pressure is 1.2×10^{-5} dynes cm^{-2}, and the ram pressure of the wind is $\sim 5 \times 10^{-5}\gamma(R_1)^{-2}$ dynes cm^{-2}. The distance of the planet from the central star is therefore implied to be of order 3 AU from these numbers.

The average vertical thickness of the toroidal disk can be estimated from the volume filling factor (given above) as 2–3×10^{11} cm ($\sim$0.02 AU at a radial distance of $\sim$20 AU). In this case the disk will absorb a fraction $\sim 3 \times 10^{-4}$ of the momentum flux carried by the wind, and the effective outward acceleration of the disk material is $\sim 3 \times 10^{-4}$ cm s^{-2}. This implies that it takes $\sim$200 yr for the ionized material to gain enough energy to carry it out of the system through the "excretion disk."

V. DISCUSSION

It should be noted that the supposed Jovian-like planet would have to have unusual properties in order to be capable of supplying the ionized plasma. If equation (3.2) applies, and the dissipation time scale given above matches the replenishment time scale, so that nebula is in steady state, then, at a planetary distance of $\sim$3 AU, the radius of the ablating object would have to be $\sim 0.6\ R_\odot$. This is essentially the same as the computed thickness of plasma toroid at its inner edge ($\sim$0.5 $R_\odot$). We cannot therefore be talking of a normal Jovian planet, but rather, of a much larger, weakly bound body. In order for the ionized plasma to freely escape, the escape velocity at the ionization front would have to be of order 10 km s^{-1}. This implies a mass for the planetary object of $\sim 5 \times 10^{29}$, which is about the same as Saturn.

Why should this object seem to be so bloated by comparison with a normal Jovian planet? In this context, it must be recalled that the central star has recently passed through the luminous giant and asymptotic giant phases. This will have had two effects. First, direct heating of the outer layers will have resulted in bloating of the outer layers of the planet. When the luminosity was thousands of times that of the Sun, this will have heated the surface to a temperature close to 2000 K, some 10 times that of the Jovian planets. Second, the planet will have captured considerable amounts of the matter ejected as a slow wind in the red giant and asymptotic giant phases. Bearing in mind the low temperature of the central star, at the distance of the supposed planet, the wind will not be ionized, and so its capture into an accretion disk about the planet will be influenced primarily by gravitational effects, rather than by the magnetic field about the planet. In this case, the capture of matter will tend to occur preferentially in the material with low angular momentum relative to the planet, in other words, the wind material in the planet's wake. The effective radius for accretion, $r_{\rm acc}$, is given approximately by,

$$r_{\rm acc} = 2GM_p/v_W{}^2\ , \tag{5.1}$$

where v_W is the velocity of the stellar wind in the giant phases, $\sim$6–10 km s^{-1}. Thus, $r_{\rm acc} \sim 1.0 \times 10^{11} M_{30}$ cm, where, as before, the mass of the planet, M_{30}, is measured in units of 10^{30} g. Since 0.5 $M_\odot$ is ejected in total in the giant phases, the mass accreted into a disk around the planet will be of order 10^{-5} $M_\odot$, assuming that the planetary distance remains constant. Livio and Soker (1984) have attempted to compute rates of accretion and or evaporation for low-mass companions close enough to be either inside the primary star's envelope or else to be affected by the wind of the giant star or both. Nearby, low mass companions are generally found to spiral inward toward the red giant core and be evaporated, whereas more massive companions survive and grow an order of magnitude in mass, finishing at an orbital separation of a few solar radii. The rate of objects with greater initial orbital radii, applicable to our scenario, was not calculated by Livio and Soker. However, it is evident that the post–main-sequence mass loss will result in an increase in orbital separation, while any accretion from the wind tends to decrease it. Of these effects, the first almost certainly dominates, since the mass loss for the central star is $\sim$50%, whereas the planet will have accreted only between 1%–10% of its initial mass. Thus, we can conclude that our planetary object is close to, or somewhat outside, its initial orbit.

Assuming that the (cold) disk has a sufficiently long lifetime against viscous dissipation, then the lifetime of this accretion disk is set by photoionization ablation. At the current luminosity of the central star this is $\sim 3 \times 10^6$ yr. Taking into account that the central star was more luminous in the past, the disk lifetime is probably comparable with the evolution time scale. Note that the stellar material is captured into a weakly bound orbit, as required, and that the composition of the material reflects that of the central star, which should be near to that of the Sun. Indeed, the slight overabundance of He derived in § II would tend to support this hypothesis. This is consistent with the helium abundances derived in some normal planetary nebulae (Kaler 1985), for which the various giant branch and AGB dredge up episodes predicted by theory (e.g., Becker and Iben 1980) seem in fact to have occurred. The possibility of an associated nitrogen enhancement cannot be confirmed from the existing data, but it would be worthwhile to make more sensitive observations in search of the [N II] lines. On the balance of the evidence we have available, the concept that nebula results from photoionization-driven ablation of a captured circumplanetary disk seems to be the most attractive of the models suggested here.

The hypothesis presented here, if correct, would seem to indicate that planetary systems may be observed in photoionization ablation around hot white dwarfs. Why then is 0950+139 the only system yet detected with a compact forbidden line emission nebula? In this context, it should be noted that there *are* two other very hot white dwarf stars which are known to exhibit peculiar narrow permitted emission lines, although it is not absolutely clear that they are a related phenomenon. The 80,000 K DO white dwarf KPD 0005+5106 shows He II, C IV, and H Balmer emission lines, despite the absence of obvious photospheric Balmer absorption (Downes *et al.* 1987). This system is particularly difficult to explain in terms of photospheric emission. The 62,000 K DA white dwarf G 191–B 2B shows a weak central reversal of the Hα line (Reid and Wegner 1988), which might be due to non–LTE effects, or even a wind (Bruhweiler and Kondo 1983). These two cases might be an effect of late time nuclear burning, either by diffusionally induced H burning (Michaud and Fontaine 1984), or by He burning, which has been suggested to power *g*-mode instabilities (Kawaler *et al.* 1986). Radiative driven mass loss from the star, or radiation pressure driven atmospheric levitation or extension has been found empirically to persist up to $\log(g) \sim 8.0$, or down to effective temperatures of 20,000 K.

The luminosity function of Fleming, Liebert, and Green (1986) has of order 10 times as many white dwarfs at 50,000 K or $L \sim 1\ L_\odot$ than at 70,000 K or $L \sim 10\ L_\odot$. Why then would these cooler stars not also be associated with similar nebulae? First, note that any Jovian planet has to be at just the right distance to accrete an appreciable disk, but not one so massive as to cause it to spiral into the central star. Therefore, even if we assume planetary systems are universal, only a fraction of these will have the right conditions for the formation of this phenomenon. Second, equation (3.2) predicts that the ablation rate scales as the luminosity, however, this will only be true as long as the ionized gas remains hot at the zone where the photons from the central star are absorbed. Once the specific intensity of the radiation field falls below $\sim 10^4$ cm s^{-1}, this will no longer be true, and the gas will remain neither very hot nor fully ionized. In this case, the ablation rate will fall rapidly and a nebula will cease to be visible against the stellar continuum. In the case of a circumplanetary disk, the emission will be further quenched by the fact that the viscous dissipation lifetime of the disk is finite, and by the fact that, as the outer portions of the disk are stripped, the ablation region will be driven to the denser, more tightly bound portions.

In the case of hotter stars, the Hβ luminosity is expected to scale as the luminosity. However, from equation (4.1), the density will also scale as the luminosity, and therefore, the forbidden lines will be completely quenched by collisional deexcitation at these higher luminosities. Thus, the permitted lines from the nebula may not be recognized as being distinct from the stellar emission lines. Furthermore, the normal planetary nebula envelope would not have had as much time to dissipate, and the plasma toroid emission might also be confused with the nebular emission.

Hot subdwarfs are stars of similar temperatures and luminosities to these considered above, but they spend a much longer time at higher luminosities. Thus, it is probable that any planetary disks have been completely stripped away in the majority of cases.

It is possible that photoionization ablation could be important in the case of close detached binary systems containing a very hot white dwarf or subdwarf? Consider the most favorable example known, BE UMa, which has a white dwarf with an effective temperature of 80,000 K, and an M dwarf companion of only 0.2 $M_{\odot}$. In this case the escape velocity from the companion is 10 times that of Jupiter, so that the gas would have to be heated to a temperature ~ 100 times higher to escape. This is just not possible, and so BE UMa has an *in situ* photoionized atmosphere (Margon, Downes, and Katz 1981; Ferguson *et al.* 1987).

Notwithstanding these caveats about the probability of detection of a similar system, it may well be worthwhile searching for emission-line evidence of Jovian planets in high-resolution spectra of hot white dwarfs and other post–AGB stars. The lower limit for the possible orbital radii (~ 2 AU) is more accurately established from the size of the primary in its AGB phase, than is the upper limit for photoionization ablation to be important. However, much theoretical work suggests that the Jovian planets would form preferentially at a few AU, and these authors are aware of one well established observational case! In any event, we hope that this paper has highlighted the need for more rigorous theoretical studies on the variety of physical processes and problems that occur in the late evolution of planetary systems.

J. L. acknowledges the useful comments from Nick Scoville and Dayal Wickramasinghe, and the hospitality of the mathematics department of the Australian National University and of Mount Stromlo and Siding Spring Observatory. J. L. also wishes to acknowledge the financial support of the US National Science Foundation, through grant AST 88-18624, and the Australian National University for the award of a Visiting Fellowship. M. A. D. wishes to thank J. L. for coming to Australia.

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