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# HM SAGITTAE AS A YOUNG PLANETARY NEBULA

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## ABSTRACT

HM Sagittae is suggested to be a very young planetary nebula recently transformed from a red-giant star through continuous mass loss. The observational data for HM Sge have been analyzed in terms of the interacting stellar wind model of planetary nebula formation. The model is in accord with virtually all the spectral data available—radio, optical, and infrared—as well as with the remarkable brightening of HM Sge observed in 1975. In particular, all three gaseous components predicted by the model are observed in the optical spectrum. The density in the newly formed shell is found to be at least $5 \times 10^7$ cm$^{-3}$, a value considerably higher than that found by the conventional analysis, which assumes a single-component homogeneous nebula. The radio spectrum is dominated by free-free emission from the remnant red-giant wind. The infrared spectrum suggests the presence of two dust components, one consisting of silicate grains left over from the red-giant stage and the other of grains newly formed after the 1975 brightening. The low observed shell mass is consistent with the interacting stellar wind model but is not consistent with the conventional sudden-ejection model of planetary nebula formation.

*Subject headings:* nebulae: planetary — stars: circumstellar shells — stars: individual

### I. INTRODUCTION

In 1975 Dokuchaeva discovered the sudden brightening of HM Sge (Dokuchaeva 1976). Within a period of 2 years, it changed from a red star of 17th mag to a star of 11th mag with an emission-line spectrum similar to that of a planetary nebula (Stover and Sivertsen 1977). Because its optical history is so similar to that of V1016 Cygni, an emission-line/radio star, it was promptly observed in the radio and was first detected by Feldman at 10.5 GHz (Feldman 1977). Since then, further radio observations of HM Sge have covered the spectral region from 2.7 to 14.9 GHz (Feldman *et al.* 1978). The radio continuum shows a V1016 Cygni–like $\nu^{+1}$ spectrum, indicating mass outflow from the star.

Infrared observations of HM Sge reported by Davidson, Humphreys, and Merrill (1978) revealed a 1000 K blackbody with a silicate feature at 10 $\mu$m, again similar to that of V1016 Cygni. Recently, Wallerstein (1978) found the optical emission-line profiles of HM Sge to show a huge disparity in width, ranging from 35 km s$^{-1}$ for [N II] to 1700 km s$^{-1}$ for H$\alpha$, indicating the existence of more than one emitting region. All the above authors suggest HM Sge to be at an early stage in the formation of a planetary nebula; however, the observations in the various spectral bands indicate a complex structure, and it has not been made clear how this is related to the planetary nebula phenomenon. This paper is an attempt to synthesize all the observations over the visual, infrared, and radio spectral bands in a particular model.

### II. MODEL

It has long been believed that a planetary nebula is formed by the sudden ejection of matter ($\sim 0.1\, \mathfrak{M}_\odot$) during the late evolutionary stages of a low-mass star. An alternative theory on the origin has recently been proposed by Kwok, Purton, and FitzGerald (1978, hereafter Paper I) in which a nebula is formed by the gentle interaction of two stellar winds over a period of several thousand years. The observed behavior of HM Sge is consistent with this latter model, which will be examined in detail.

In Paper I it is suggested that a stellar wind flows from the precursor red giant, driven by radiation pressure on the dust in its atmosphere. Dust is expected to form in the low-temperature environment provided by a red giant, and as it is pushed radially outward, it drags the gaseous atmosphere with it (Kwok 1975). Over the lifetime of a red giant, an extensive circumstellar envelope of appreciable mass accumulates. Such envelopes have been detected in many late-type giants (through infrared and microwave observations), and their remnants have also been observed in three planetary nebulae (Mufson, Lyon, and Marionni 1975). The detection of molecular hydrogen in five planetary nebulae (Beckwith, Persson, and Gatley 1978) further confirms the association of neutral material with planetary nebulae.

If mass loss continues until the hot core of the red giant is exposed, radiation pressure on the now ionized gas becomes the dominant repulsive force, resulting in a large increase in ejection velocity. Collision of this new high-velocity wind with the remnant of the red-giant wind produces a dense shell of gas at the interface. As the shell expands, photoionization finally overcomes recombination and dust attenuation, and an emission-line spectrum emerges. The event may be observed photometrically as a brightening of several magnitudes. Ionization beyond the shell in the remnant of the red-giant envelope produces free-free continuum radiation that may be observed in the radio. Dust both in the shell and in the remnant envelope would together produce a broad spectrum of infrared radiation. All these predicted features are observed in V1016 Cyg and HM Sge.

The changeover from the old wind to the new wind takes place fairly rapidly. This is to be expected, as conditions in the core and in the envelope are quite insensitive to the envelope mass until it has reached quite small values, certainly as low as $10^{-3}\,\mathfrak{M}_\odot$ and perhaps as low as $10^{-5}\,\mathfrak{M}_\odot$ (Paczyński 1974). Given the mass-loss rate in the red-giant phase, the time scale for the final stages of ejection is then of the order of years. When the envelope mass has been reduced below the critical value, the star will cease to be a red giant: the small remnant atmosphere will be ionized by high-energy photons from the core, and the dominant mechanism of mass ejection will change abruptly.

The model summarized above predicts that a very young planetary nebula should have three gaseous components contributing to the observed spectrum: the remnant of the red-giant wind, the high-velocity wind from the central star, and the shell formed at the interface of the two winds, all of which are ionized by radiation from the central star. The presence of these three components in the spectrum of HM Sge is shown clearly by Wallerstein's line-width measurements (Wallerstein 1978), which indicate three distinct velocity components. The low-velocity ($\sim 35$ km s$^{-1}$) component is observed in forbidden lines which are quenched at high densities and may be identified with the remnant wind. The intermediate-velocity ($75 \pm 20$ km s$^{-1}$) component is observed in lines of higher critical density and may be identified with the shell. The high-velocity ($\sim 1700$ km s$^{-1}$) component is observed only in H$\alpha$ and may be identified with the high-velocity wind from the nucleus.

The above model also suggests that as the planetary nebula develops, the shell increases in size and mass and in time dominates the emission from the system. If the other components of the system are to be observed, it must be done when the planetary nebula is young and the shell small. In the early stages the spectrum will reflect the complexity of the system and provide information on the formation process. HM Sagittae is believed to be just such a system.

In the following, each spectral region for HM Sge is considered in turn and an attempt is made to interpret the observations in terms of the interacting stellar wind model.

### III. RADIO SPECTRUM

In this section we argue that the radio emission observed in HM Sge arises from free-free emission in the remnant envelope of the precursor red giant. From the observed radio flux, the mass-loss rate of this red-giant wind is derived. Using the interacting stellar wind model, the mass and density of the newly formed gas shell are then calculated.

The present status of radio continuum observations of HM Sge is summarized in Feldman *et al.* (1978). There have been measurements at six frequencies between 2.7 and 14.9 GHz, all obtained around mid-1977. The observed spectrum has a spectral index of approximately +1, which indicates that the radio emission must originate from a stellar wind and not from a shell of uniform-density gas (Seaquist and Gregory 1973). Since the angular size at the $\tau = 1$ level is much larger in the remnant red-giant wind than in the new wind from the nucleus (for any reasonable parameters), the observed radio emission must come predominantly from the red-giant wind.

In this type of radio spectrum the flux level is determined by $\dot{\mathfrak{M}}/V$ (ratio of the mass-loss rate to the velocity of the wind) and the distance (Wright and Barlow 1975). Assuming $T_e = 10^4$ K and adopting Wallerstein's value of $V = 35$ km s$^{-1}$, $\dot{\mathfrak{M}}$ for the red-giant wind is found to be $\sim 2 \times 10^{-6}\, D^{3/2}\,\mathfrak{M}_\odot\,\text{yr}^{-1}$, where $D$ is the distance in kpc. No accurate information is available on the mass-loss rate from the central star ($\dot{m}$); however, the known shell expansion velocity of $75 \pm 20$ km s$^{-1}$ and the analysis of Paper I provide a reasonable estimate of $10^{-8}$–$5 \times 10^{-7}\,\mathfrak{M}_\odot$ yr$^{-1}$ for a distance of 500–2500 pc.

Parameters of the shell cannot be estimated without knowledge of when the red-giant wind stopped and the central-star wind began (taken as $t = 0$). Since the star is known to have brightened in 1975, the epoch at which the radio measurements are made (mid-1977) cannot be less than 2 yr. Comparison of the photoionization and recombination rates shows that the shell should be ionized shortly after the red-giant wind stops (detailed calculations on ionization are presented in § VI). An epoch of 2–3 yr and an expansion velocity ($V_s$) of $75 \pm 20$ km s$^{-1}$ would give the shell a radius ($R_s$) of $\sim 6(\pm 3) \times 10^{14}$ cm. The mass of the shell cannot be calculated to a high degree of accuracy because the linear increase in mass (as discussed in Paper I) applied when the evolution of the planetary nebula has settled to a steady state. However, a rough estimate gives a minimum shell mass of $10^{-5}\, D^{3/2}\,\mathfrak{M}_\odot$. At this early stage the shell is compressed by the high pressure of the stellar winds and remains relatively dense. A value of $5(\pm 2) \times 10^7\, D^{3/2}$ cm$^{-3}$ is obtained for the hydrogen density by balancing the external dynamic pressure

$$p = \frac{\dot{\mathfrak{M}}(V - V_s)^2}{4\pi R_s^2 V}$$

(with values for the parameters taken from above) to the internal thermal pressure [$p = (n_i + n_e)kT_e$, $T_e = 10^4$ K]. The emission measure in the shell ($n_e^2 V$, where $V = 4\pi R_s^2 \Delta R_s$, $\Delta R_s$ as calculated in eq. [7] of Paper I) is found to be $10^{59}$–$10^{60}\, D^3$ cm$^{-3}$. This can be compared to the emission measure in the remnant red-giant envelope, given by

$$\int_{R_s}^{\infty} n_e^2 dV = \frac{4\pi A^2}{R_s} \approx 5 \times 10^{58}\, D^{3/2}\ \text{cm}^{-3}\,,$$

where $A = n_e r^2 = \dot{\mathfrak{M}}/4\pi\mu m_{\rm H} V$; $\mu$ and $m_{\rm H}$ are the mean atomic weight and mass of a hydrogen atom, respectively. The emission measure in the new high-velocity wind, calculated from the same expression as given above, is found to be $\sim 1 \times 10^{56} D^{3/2}$ cm$^{-3}$, much smaller than in the other components.

All three gaseous components (the remnant of the red-giant wind, the shell, and the central-star wind) emit free-free radiation in the radio, but the values of $n_e{}^2 V$ calculated above suggest that (1) radiation from the central-star wind is negligible compared to that from the red-giant wind, and (2) at high frequencies, where both the shell and the red-giant wind are optically thin, radiation from the shell dominates. At low frequencies, where both components are optically thick, the contribution from the shell is limited by its small size and the wind dominates. The shell parameters derived above suggest that the shell is optically thick for frequencies less than 100 GHz, well above the highest observing frequency. These conclusions are consistent with the initial argument, based on the slope of the observed spectrum, that radio radiation in the observed frequency range is produced predominantly in the remnant red-giant wind.

Figure 1 shows the expected evolution of the radio spectrum, calculated for $D = 1$ kpc. From equations (5), (6), and (7) of Paper I, we have $\mathfrak{M}_s \propto t$, $R_s \propto t$, and $\Delta R_s \propto t$; therefore, $n_e \propto t^{-2}$ and $(n_e{}^2 V)_s \propto t^{-1}$. The emission measure in the red-giant envelope, being inversely proportional to $R_s$, also decreases linearly with time. Thus, as the shell expands, both the shell and the remnant envelope will become optically thin at increasingly lower frequencies, and radiation from the shell will dominate that from the envelope at progressively lower frequencies. This effect is clearly seen in Figure 1, which shows the result of a full radiative transfer calculation and includes the contributions from all three components of the system. After several decades the remnant of the red-giant wind will become totally unobservable in the radio and the radio spectrum will resemble that of a typical planetary nebula.

Finally, we should note that the shell parameters are based on the assumption that $\mathfrak{M}_s = 0$ at $t = 0$. This is clearly an idealization, for we expect a small remnant atmosphere above the core after the change-over from the old wind to the new wind (see § II). This will in effect increase our estimate for $\mathfrak{M}_s$ and $(n_e{}^2 V)_s$, and therefore the relative contribution from the shell to the radio flux. Since the high-frequency emission is coming predominantly from the shell, the predicted flux level above $\nu = 10^{12}$ Hz shown in Figure 1 must be considered a lower limit.

## IV. OPTICAL SPECTRUM

In this section the emission-line spectrum is discussed and interpreted in terms of the interacting stellar wind model. Some of the emission lines arise in the remnant red-giant wind and some in the newly formed shell, depending in each case on the critical density associated with the line. From this we show that the line-width measurements of Wallerstein are in excellent agreement with the model. It is also emphasized that the interpretation of forbidden-line intensity ratios must be approached with caution in a system composed of several gaseous components and, in particular, where the density distribution is

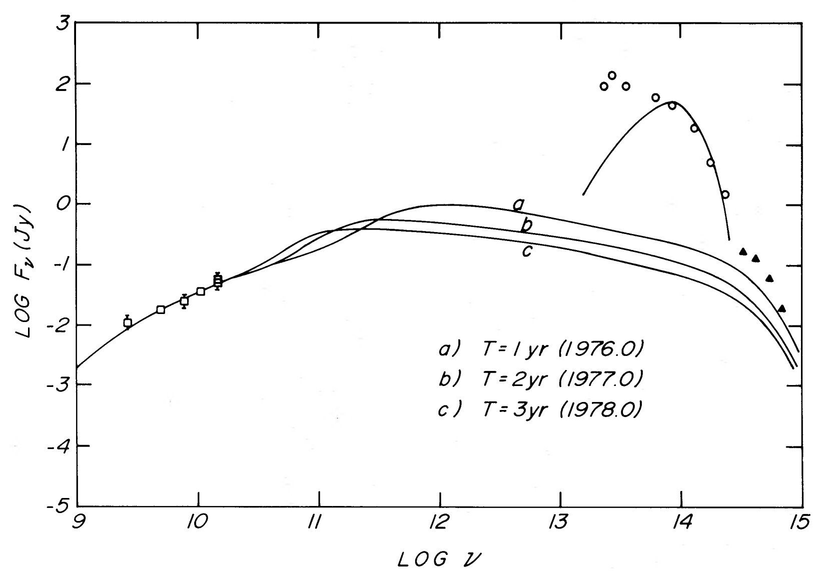


FIG. 1.—Spectrum of HM Sge showing radio, infrared, and visible data. *Triangles*, continuum measurements (emission lines removed) by Davidson *et al.* uncorrected for reddening; *open circles*, infrared photometry by Davidson *et al.*; *squares*, radio observations from Feldman *et al.* (1978). The curve drawn through the infrared data is the emission spectra for pure graphite grains of size 0.01 $\mu$m and temperature 800 K. The curves drawn through the radio data represent the theoretical free-free spectrum at three different epochs. The parameters adopted are $D = 1$ kpc, $\dot{\mathfrak{M}} = 2 \times 10^{-6} \mathfrak{M}_\odot$ yr$^{-1}$, $\dot{m} = 6 \times 10^{-8} \mathfrak{M}_\odot$ yr$^{-1}$, $V = 35$ km s$^{-1}$, and $v = 1700$ km s$^{-1}$. The mass of the shell is assumed to be zero at $t = 0$. The size of the ionized region of $4.5 \times 10^{15}$ cm is used to reproduce the observed spectral index of $\sim 0.9$.

nonuniform. The observations of Ciatti, Mammano, and Vittone (1978, hereafter CMV78) and Davidson *et al.* are discussed from this viewpoint. Finally, a suggestion for the long-term evolution of the emission-line spectrum is proposed.

The model in Paper I proposes that three distinct gaseous components be present in a young planetary nebula. The optical observations of HM Sge made by Wallerstein (1978) distinguish the three gaseous components in that system by the different expansion velocities found for each, which were used in § III to obtain estimates of the parameters for the two stellar winds and for the shell formed at the interface. Using these parameters, it was shown in § III that $\int n_e^2 dV$ is greatest in the shell component ($10^{59}$–$10^{60}$ $D^3$ cm$^{-3}$), less in the remnant red-giant wind ($5 \times 10^{58}$ $D^{3/2}$ cm$^{-3}$), and much less in the new high-velocity wind ($1 \times 10^{56}$ $D^{3/2}$ cm$^{-3}$). In general, then, it might be expected that the observed emission lines arise primarily in the shell. However, if the effects of collisional de-excitation are included, then only lines of high $n_c$ will be seen in the shell while the remnant wind component will dominate for lines of low $n_c$. Further, only permitted lines will be expected in the high-velocity wind because of the high densities, and those can be distinguished from the much greater shell contribution only by virtue of their much greater width. These general characteristics are indeed displayed in the measurements reported by Wallerstein.

Specifically, the full width of the lines from the high-velocity wind is seen by Wallerstein only in Hα, the most intense permitted line. The only other permitted line noted by him is He I λ6678, which shows a maximum width much less than that of Hα but a greater width than the forbidden lines. As the expected intensity of the He I λ6678 line is only ~1% of Hα, it is likely that the broad wings of the He I were simply not observed to their full extent. The high-velocity wind has also been observed by Davidson *et al.* and CMV78. The latter refer to it as a Wolf-Rayet phenomenon and derive a velocity similar to that of Wallerstein.

The forbidden line of highest critical density ($n_c$) observed by Wallerstein, [S III] λ6312, yielded an expansion velocity of $75 \pm 20$ km s$^{-1}$, while those of lowest $n_c$, [N II] λ6548 and λ6584, yielded the lower velocity of 35 km s$^{-1}$; these were interpreted as the shell and remnant red-giant wind velocities, respectively. The [O I] lines (λ6300 and λ6363), with an intermediate $n_c$, had a width slightly less than that of the S III line. The production and excitation of O I lines has been a long-standing problem in the study of planetary nebulae and will not be considered further here.

The difficulty of determining electron densities from forbidden-line intensity ratios in a complex system such as HM Sge must be emphasized. The danger of applying the conventional analysis (see, e.g., Osterbrock 1974) to an inhomogeneous nebula has been foreseen by Panagia and Preite-Martinez (1975) in their analysis of an inverse-square density profile. In the case of HM Sge the presence of three gaseous components has been clearly demonstrated by Wallerstein's observations, and the analysis must be based on a more realistic model than that of a homogeneous nebula. The relative intensities of forbidden lines may be interpreted through the values of the effective $n_e^2 V$ of the shell and the remnant wind. If one allows for the effects of quenching (through the critical density $n_c$), the effective $n_e^2 V$ are given by

$$\text{eff}\,(n_e^2 V)_s = \frac{4\pi R_s^2 \Delta R_s n_e^2}{1 + n_e/n_c} \quad (1)$$

for a thin shell of radius $R_s$, thickness $\Delta R_s$, and uniform electron density $n_e$, and

$$\text{eff}\,(n_e^2 V)_{\text{wind}} = 4\pi A^{3/2} n_c^{1/2} \tan^{-1}\left(\frac{A^{1/2}}{R_{\text{IN}} n_c^{1/2}}\right) \quad (2)$$

for an extended envelope with inner radius $R_{\text{IN}}$. In a low-density homogeneous gas the [O III] line intensity ratio, $I_{4959} + I_{5007}/I_{4363}$, is approximately 200 (Osterbrock 1974), but for the present model the ratio must be decreased by a factor

$$[\text{eff.}\,(n_e^2 V)_s(n_c = 6 \times 10^5\ \text{cm}^{-3}) + \text{eff.}\,(n_e^2 V)_{\text{wind}}(n_c = 6 \times 10^5\ \text{cm}^{-3})] \times [\text{eff.}\,(n_e^2 V)_s(n_c = 2 \times 10^7\ \text{cm}^{-3}) + \text{eff.}\,(n_e^2 V)_{\text{wind}}(n_c = 2 \times 10^7\ \text{cm}^{-3})]^{-1}.$$

Using the parameters derived in § II and choosing $D = 1$ kpc, we find the predicted line intensity ratio to be ~15 (in fact, the predicted ratio is fairly insensitive to the distance chosen), in contrast to the value of ~5 observed by CMV78 or the reddening-corrected value of ~8 reported by Davidson *et al.* This result suggests that the effective value of $n_e^2 V$ in the shell has, if anything, been underestimated by the model. This is consistent with the suggestion in § III that $\mathfrak{M}_s \geq 0$ at $t = 0$.

Both Ciatti, Mammano, and Vittone (1977, hereafter CMV77) and Davidson *et al.* have used the [O III] intensity ratios to derive a density in the "nebula," assuming that all the lines arise in the same gaseous component. If in fact the observed [λ4959] and [λ5007] lines are produced in the remnant wind, then they must be even more heavily quenched in the shell than the above authors suspected and the densities that they derived must be taken as lower limits for the density in the shell. The value of $5 \times 10^7$ cm$^{-3}$ suggested above is indeed higher than the density obtained by them.

There has been one report of a P Cygni effect in the spectrum of HM Sge (Wallerstein 1978). Note that the column density ($A/R_{\text{IN}}$ for the winds [where $R_{\text{IN}}$ is the radius at the base of the flow] and $n_e \Delta R$ for the shell) is greatest in the remnant red-giant wind (in contrast to the value of $\int n_e^2 dV$, which is greatest in the shell). The effect is seen in the He I λ6678 line, at a wavelength corresponding to the velocity of the remnant wind, in agreement with the model.

If the He I atoms provide appreciable absorption, then similar effects may be expected in the hydrogen lines. When one considers the velocity difference between the shell and the surrounding remnant wind, as well as the usual radiative transfer problems of spherical expansion, any simple interpretation of the Balmer decrement based on a homogeneous static or a simple moving envelope model must be viewed as inadequate.

If a planetary nebula develops as suggested in Paper I, then the long-term changes in the optical emission-line spectrum of HM Sge can be predicted. Since $(n_e^2 V)_s \propto t^{-1}$ (see § III), lines which are not quenched in the shell, primarily the permitted lines, should decrease in intensity almost linearly with time (although the shell increases in mass, the increase in size and the assocated decrease in $n_e$ dominate). In the early stages of development, lines which are quenched in the shell should increase in intensity roughly linearly with time. Lines of low $n_c$ which arise primarily in the remnant wind would be expected to decrease in intensity, accompanying a linear increase in $R_s$ (eq. [2]) with time, until the intensity of the same line from the shell becomes greater. These considerations suggest an interesting evolution of line intensities over a long time. If the relative intensities of the shell lines and the remnant wind lines observed in 1976 by CMV77 and in 1977 by Davidson *et al.* are compared, there is a suggestion that the forbidden lines in the shell have increased relative to the lines in the remnant wind, as expected. However, the importance of appreciable changes in the system in a short time has been noted by CMV78, and a longer time base is needed before any of the suggested long-term changes can be observed with any confidence.

## V. INFRARED SPECTRUM

In this section we show that the infrared spectrum of HM Sge is emitted by two dust components: one from silicate dust in the remnant red-giant envelope and one from graphite dust newly condensed after 1975. The total number of graphite grains calculated from the absolute flux is then compared to the mass of the shell obtained in § IV, and the gas-to-dust ratio is found to be reasonable.

The infrared spectrum of HM Sge was obtained by Davidson, Humphreys, and Merrill (1978) in 1977 June. The energy distribution is essentially that of a 1000 K blackbody with 1.7 mag of excess silicate emission peaking at 9.7 $\mu$m. Narrow-band spectrophotometry between 10 and 13 $\mu$m confirms the existence of silicate grains. The most interesting feature of the spectrum is its overall broadness, uncommon among infrared stars but strikingly similar to V1016 Cyg. The detection of silicate grains is not unexpected, for they are commonly found in circumstellar envelopes of oxygen-rich (O/C > 1) late-type giants (Woolf and Ney 1969; Gilman 1969). This implies that the precursor red giant of HM Sge is likely to have been oxygen rich rather than carbon rich. The presence of a silicate feature is unusual in a planetary nebula, but in this case is consistent with the suggestion that HM Sge is in transition between a red giant and a planetary nebula.

Assuming that the infrared emission is optically thin, the energy distribution is directly proportional to the emissivity of the grain material. Gilman (1974) has calculated the emissivity of silicates and found that although their spectra show strong features at 10 and 20 $\mu$m, they emit extremely inefficiently in the near-infrared. It is unlikely then that silicates are responsible for the blackbody radiation observed in HM Sge between 2 and 8 $\mu$m. The implication is that a second component of dust grains of some other chemical composition may be present, which probably has formed fairly recently in the new shell. As the shell will eventually dominate the system, this conclusion is consistent with a previous suggestion that the dust grains observed in planetary nebulae in general are not silicates (Woolf 1973). Also, the formation of dust grains in ionized gas has been observed both in novae (Ney and Hartfield 1978) and near the central stars of at least two planetary nebulae (Cohen and Barlow 1974; Cohen *et al.* 1977). Apparently, dust condensation can occur in an ionized environment provided the equilibrium temperature is less than the condensation temperature. The conclusion is that the infrared spectrum of HM Sge can be explained by two components, one due to silicate dust left over from the red-giant phase and the other due to grains in the shell, newly formed in the past few years. The chemical composition of the latter is uncertain, but they may be graphite grains, as suggested by the lack of emission features and by the high condensation temperature and simple structure of graphite. The presence of dust in WC stars but not in WN stars also suggests that the dust grains that condense in an ionized environment are likely to be graphite (Cohen, Barlow, and Kuhi 1975).

If most of the new grains are located in the shell, then their temperature must be approximately uniform. The shell is undoubtedly optically thin in the infrared because an optical depth greater than 1 in the infrared implies an optical depth greater than $\sim 100$ in the UV, in conflict with the existence of an ionized envelope outside the shell. We have fitted the infrared observations by a shell of 800 K graphite grains (Fig. 1) using the emissivity of pure graphite calculated by Gilman (1974). The fitting shortward of the silicate bump and longward of 1.25 $\mu$m is reasonable except for the 4.9 $\mu$m point which is found to be above the calculated spectrum. This suggests that the emissivity of the grain has a weaker dependence on wavelength than does that of pure graphite. The number of grains required to account for the observed flux level can be calculated and is found to be $\sim 5 \times 10^{41} D^2$ (for $a = 0.01$ $\mu$m). By adopting normal cosmic abundances for carbon, the total shell mass is then estimated to be $6 \times 10^{-7} D^2 \mathfrak{M}_\odot$, less than the $10^{-5} \mathfrak{M}_\odot$ estimated in § II, indicating that there has not been total condensation of the carbon atoms.

The observed flux at 1.25 $\mu$m is clearly above the thermal spectrum expected from dust grains. The excess cannot be explained by another dust component, for the required temperature would be too high. Such an excess of near-infrared radiation is not unique to HM Sge but in fact has been observed in V1057 Cyg and FU Ori, for example (cf. Herbig 1977). From Figure 1 we can see that the free-free continuum from the ionized gas contributes only about 10% of the observed flux at 1 $\mu$m and therefore cannot be responsible for the excess. However, if there were a remnant atmosphere of appreciable mass (say, $10^{-4}\,\mathfrak{M}_\odot$, see discussions in §§ II and III) at $t = 0$, then the free-free continuum could be significant. A free-free continuum at such a level is not inconsistent with the measured optical continuum (Davidson *et al.*) with a reasonable reddening correction.

Emission from the silicate grains is not as easy to calculate because an appreciable optical depth at 10 $\mu$m requires a full radiative transfer treatment and because the grain temperature is expected to vary with distance from the central star. Also, the possibility that the silicate grains are contaminated by other ions has to be considered, as this seems to be the case in late-type stars (Jones and Merrill 1976). This would have an appreciable effect on the spectrum, particularly the 4–8 $\mu$m region. The general features of the spectrum are those of silicate emission, but it is difficult to be more precise than that.

One might ask whether the mixture of graphite and silicate may cause absorption at 10 $\mu$m (instead of emission) as suggested by Jones and Merrill. The answer to this question lies in the nature of the heating source, which in this case is a hot star rather than the cool star in the cases considered by Jones and Merrill. Silicate grains, although relatively transparent in the near-infrared, are good absorbers of UV light. Since the central star emits most of its photons in the UV, the silicate grains will not be cooler than the graphite grains and the 10 $\mu$m feature should be seen in emission.

## VI. OPTICAL HISTORY

In this section a number of different features of the system are discussed. In § VI*a* it is shown that the observed brightening of HM Sge can be explained as the ionization of the expanding shell. Properties of the central star are then calculated and are found to be quite similar to those of planetary nebula nuclei. In § VI*b* it is shown that the circumstellar extinction implied by the model is compatible with the pre-brightening observation of HM Sge. In § VI*c* the distance problem is discussed and limits of 400–3000 pc are suggested.

### *a) Brightening Process and Properties of the Central Star*

In §§ III–IV we analyzed the optical, radio, and infrared spectra of HM Sge and concluded that all the observed radiation is circumstellar in origin. From the overall spectrum shown in Figure 1 it can be seen that infrared is the dominant region of the observed spectrum. The most obvious interpretation is that the dust grains are absorbing optical and UV continuum photons from the central star and reemitting them in the infrared. The ionization process therefore depends not only on the gas surrounding the star but also on the dust.

The optical depth in the UV due to dust absorption is given by the sum of two components, viz.,

$$\tau_{\rm UV} = \tau_s + \tau_{\rm wind} = (\pi a^2 n_s + \pi a'^2 n_s')\Delta R_s + \frac{\pi a^2 B}{R_s}\,, \qquad (3)$$

where $n_s$ and $n_s'$ are, respectively, the silicate and graphite grain densities in the shell (recall that silicate grains in the remnant envelope are swept up by the shell and that new grains are continuously forming in the shell) and $B = n_d r^2$ ($n_d$ is the silicate grain density in the wind). Assuming a constant gas-to-dust ratio in the shell and in the remnant wind, then $n_s \propto t^{-2}$ and $n_s' \propto t^{-2}$; also, $\Delta R_s \propto t$ and $R_s \propto t$ (see Paper I); so

$$\tau_{\rm UV} \propto t^{-1}\,.$$

Dust attenuation in fact decreases with time. In the early stages of development the shell density is so high that recombination and dust attenuation overcome photoionization and the shell remains neutral. At a later epoch when the shell density is lower, part or all of the shell is ionized. The transition is marked by the emergence of emission lines, signaling a large increase in the escape of optical photons, which will be observed as a sudden brightening.

As the central star is not directly observed, its properties must be derived from the spectra of the circumstellar gas and dust. Davidson *et al.* have estimated the observed flux between 2 and 8 $\mu$m to be $6 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$, with the possible addition of $3 \times 10^{-8}$ ergs cm$^{-2}$ s$^{-1}$ if the 10 and 20 $\mu$m silicate features are included. The total flux due to free-free emission from the gas can be calculated from the $n_e^2 V$ estimated in § II and is found to be about 1% of the infrared flux. Therefore, we can safely assume that the total emergent flux consists of two components: infrared radiation from the dust and attenuated starlight. The large difference between the stellar and dust temperatures ensures that these two components are clearly separated and do not overlap in frequency. Assuming that the optical depth is frequency independent over the stellar continuum, the infrared flux is $\sim[1 - \exp(-\tau_{\rm UV})] \times$ stellar flux. Using the number of dust grains estimated in § V, we have, very crudely,

$$\tau_{\rm UV} \approx (D^2)(t/2.5\ {\rm yr})^{-1}\,. \qquad (4)$$

This suggests that for $D = 1$ kpc, the IR flux represents roughly half of the total flux and the stellar luminosity can be as high as 4500 $L_\odot$. For $D = 2$ kpc, $\tau_{\rm UV}$ must be larger, as more grains are required to account for the observed IR flux, and $L_* \approx 10^4\,L_\odot$. The effective temperature of the central star has been estimated by Davidson *et al.* to be at least 50,000 K. The corresponding stellar radii are $R_* \lesssim 0.9\,R_\odot$ (for $D = 1$ kpc) and $R_* \lesssim 1.3\,R_\odot$ (for $D = 2$ kpc), typical of planetary nebula nuclei.

From the model atmospheres for planetary nebula nuclei calculated by Hummer and Mihalas (1970), the total number of photons with $\lambda < 912$ Å emitted per second ($S$) is found to be only weakly dependent on the effective temperature of the star if $T_* > 50{,}000$ K. As this condition is likely to be true in HM Sge, $S$ is approximately $3 \times 10^{47}$ photons $s^{-1}$ at $D = 1$ kpc and $8 \times 10^{47}$ photons $s^{-1}$ at $D = 2$ kpc. Using the shell mass and electron density calculated in § III, and the dust density calculated in § V, we find that the shell should be totally ionized at $t \approx 0.5$ yr, corresponding to the observed brightening of HM Sge in 1975 (see Appendix).

### b) *HM Sagittae before 1975*

Since the precursor red giant was surrounded by an extensive dust envelope, circumstellar reddening must have been present before 1975. Using the red-giant mass-loss rate ($\dot{\mathfrak{M}}$) derived in § III, the amount of circumstellar reddening can be estimated. Assuming that the dust and gas were uniformly mixed, the total optical depth of the envelope in the visual would have been

$$\tau_v = \int_{R_{\rm RG}}^{\infty} Q_v \pi a^2 n_d(r) dr = \frac{\pi a^2 B}{R_{\rm RG}} , \quad (5)$$

where $Q_v$ is the absorption/emission efficiency factor and has been assumed to be unity. If the dust-to-gas ratio is constant ($B \propto \dot{\mathfrak{M}} a^{-3}$), then

$$\tau_v \propto a^2(\dot{\mathfrak{M}}/a^3)(T_{\rm RG}{}^2/L_*{}^{1/2}) ,$$

where $T_{\rm RG}$ is the surface temperature of the red giant. Since $\dot{\mathfrak{M}}$ is a function of distance ($\dot{\mathfrak{M}} \propto D^{3/2}$, eq. [7] of Wright and Barlow 1975), we can write

$$\tau_v \propto D^{3/2} a^{-1} T_{\rm RG}{}^2 L_*{}^{-1/2} . \quad (6)$$

Again assuming silicate grains, a distance $\sim 1$ kpc, and a constant luminosity for the star, we have

$$\tau_v \approx 8\left(\frac{T_{\rm RG}}{2500\ {\rm K}}\right)\left(\frac{0.1\ \mu{\rm m}}{a}\right) , \quad (7)$$

which shows that a significant amount of extinction was present before 1975 ($A_v \approx 9$).

The circumstellar extinction can also be estimated from the apparent magnitude before brightening. It was shown earlier than for $D = 1$ kpc, $L_* \approx 4500\ L_\odot$, which corresponds to a bolometric magnitude of $M_B = -4 \cdot 5$, quite reasonable for a red giant. Depending on whether the star was of early or late M type, the bolometric correction could be anywhere in the range $-2$ to $-6$ mag (Lang 1974), and the visual magnitude (before extinction) between $m_v = 7$ and $m_v = 11$. Comparing this with the observed magnitude of 17 in 1950 (Dokuchaeva 1976), we arrive at an extinction of 6–10 mag. Even if allowance is made for interstellar absorption, this is in reasonable agreement with the estimated extinction given in equation (7).

### c) *Distance Problem*

In this paper we have left the distance of HM Sge as an open parameter but in several instances adopted $D = 1$ kpc for convenience in the calculation of numerical results. However, a large distance ($D > 3$ kpc) is inconsistent with the model, for the high luminosity ($L_* = 2.5 \times 10^4\ L_\odot$ at $D = 3$ kpc) would then not be consistent with the Harman-Seaton sequence, where most planetary nebula nuclei lie.

The determination of a lower limit to distance is not as simple. Appealing again to the Harman-Seaton sequence, we find that the luminosity of the central star cannot be much less than $5 \times 10^3\ L_\odot$, but this is difficult to relate to the observed flux because $\tau_{\rm UV}$ is small at small distances (see eq. [4]) and the infrared luminosity may not represent the total luminosity of the star. However, as all other spectral bands have been observed, the remaining photons must be in the UV, and taking a maximum temperature for the central star of $10^5$ K, we find that the UV flux cannot represent more than 90% of the total flux. This sets an upper limit of $10 \times$ IR flux $\approx 10^{-6}$ ergs $cm^{-2}$ $s^{-1}$ on the total flux from HM Sge, which, with a minimum luminosity of $5 \times 10^3\ L_\odot$, implies a minimum distance of 400 pc.

## VII. CONCLUSIONS

We suggest that HM Sge is a very young planetary nebula, recently transformed from a red giant through continuous mass loss. The radio, optical, and infrared spectra of the star have been analyzed in terms of the interacting stellar wind model of planetary nebula formation. The following conclusions can be drawn:

1. All three gaseous components predicted by the interacting stellar wind model are observed in the optical spectrum of HM Sge. The remnants of the red-giant wind and of the central-star wind are found to be expanding at 35 km $s^{-1}$ and 1700 km $s^{-1}$, respectively. At their interface a high-density shell can be seen expanding at 75 km $s^{-1}$.

2. Forbidden-line intensity ratios suggest a density in the newly formed shell of at least $5 \times 10^7$ $cm^{-3}$, a value which is considerably higher than that found by the conventional analysis, which assumes a single-component constant-density nebula.

3. The radio spectrum of HM Sge is dominated by free-free emission from the remnant red-giant wind. The mass-loss rate of the progenitor red giant can be calculated from the radio spectrum and is found to be $\sim 2 \times 10^{-6}\ D^{3/2}\ \mathfrak{M}_\odot\ {\rm yr}^{-1}$. Radio emission from the shell below 15 GHz was weak in 1977 but should be observable in the future as the shell expands.

4. The infrared spectrum can be explained by the presence of two dust components. The 10 $\mu$m component is emitted by silicate grains in the red-giant wind, and the 2–8 $\mu$m component by grains (possibly graphite) recently condensed in the shell.

5. The low mass of the shell ($10^{-3}\ \mathfrak{M}_\odot$ [Davidson *et al.*]) is consistent with the interacting stellar wind model, which suggests that the mass of the shell will increase with time, but is inconsistent with the

conventional sudden-ejection model of planetary nebula formation, where a much larger mass ($\sim 0.1$ $\mathfrak{M}_\odot$) is supposed to be ejected at once.

6. The sudden brightening of 6 mag and the emergence of emission lines in 1977 are the result of the penetration of the gas shell by the ionization front. The luminosity ($0.5$–$1 \times 10^4 L_\odot$) and the temperature ($T_e \gtrsim 50{,}000$ K) of the central star are both typical of those of young planetary nebula nuclei.

The detailed analysis of HM Sge presented in this paper identifies a new class of objects (very young planetary nebulae) which are spectroscopically quite different from an evolved planetary nebula. Such an identification allows us to examine more critically the theories of planetary nebula formation, which in turn may have profound effects on our understanding of the late stage of stellar evolution.

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## APPENDIX

## IONIZATION OF THE SHELL

The HM Sge system can be approximated by a central star, a high-velocity wind, a uniform-density shell, and a low-velocity wind. The attenuation of UV photons from the central star is determined by dust absorption and recombination of these three components, viz.,

$$\frac{d}{dr} S(r) = -4\pi r^2 n_e^2 \alpha^{(2)} - \pi a^2 n_d Q_{\rm UV} S(r)\,, \tag{A1}$$

where $S(r)$ is the total number of UV photons flowing through radius $r$ per second and $\alpha^{(2)}$ is the recombination coefficient for all levels with $n > 2$. In the two wind components where the number density of both gas and dust fall off as $1/r^2$ ($n_e = A/r^2$, $n_d = B/r^2$), the solution to equation (A1) can be written as

$$S(r) = [S(R_0) + S_c] \exp\left[\pi a^2 B\left(\frac{1}{r} - \frac{1}{R_0}\right)\right] - S_c\,, \tag{A2}$$

where $R_0$ is the distance to the base of the flow, $S_c = 4A^2\alpha^{(2)}/a^2 B$, and $Q_{\rm UV} = 1$.

Two types of grain coexist in the shell. If $C \equiv \pi a^2 n_d + \pi a'^2 n_d'$ and $\Delta R_s \ll R_s$, we have

$$S(R_2) = S(R_1) \exp(-C\Delta R_s) - \frac{4\pi n_e^2 \alpha^{(2)}}{C} \times \left\{R_2^2 - R_1^2 \exp(-C\Delta R_s) - \frac{2}{C}[R_2 - R_1 \exp(-C\Delta R_s)] + \frac{2}{C^2}[1 - \exp(-C\Delta R_s)]\right\}, \tag{A3}$$

where $R_1$ and $R_2$ are, respectively, the inner and outer radius of the shell. Under the interacting stellar wind model (Paper I), $\Delta R_s \propto t$ and $C$ (approximately proportional to the density of the shell) $\propto t^{-2}$; therefore, $C\Delta R_s \propto t^{-1}$ and $S(r)$ will increase with time. The shell will be ionized when $S(R_2) > 0$. As $t \to \infty$, $C\Delta R_s \to 0$ and equation (A3) reduces to the conventional results for a Strömgren sphere.

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*Note added in proof.*—Recent high-resolution IR spectrophotometry of HM Sge by R. C. Puetter, R. W. Russell, B. T. Soifer, and S. P. Willner (1978, *Ap. J.* [*Letters*], **223,** L93) shows absorption features of CO and $H_2O$ which they interpret to indicate the presence of a cool star. Their continuum spectrum is similar to the broad-band measurement of Davidson *et al.* and is not obviously incompatible with the two-component dust model. A full radiative transfer calculation is currently being performed to decide between their reddened cool star model and the two-component model of this paper.

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