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Dust formation above cool magnetic spots in evolved stars

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ABSTRACT

We examine the structure of cool magnetic spots in the photospheres of evolved stars, specifically asymptotic giant branch (AGB) stars and R Coronae Borealis (RCB) stars. We find that the photosphere of a cool magnetic spot will be above the surrounding photosphere of AGB stars, which is the opposite of the situation in the Sun. This results from the behaviour of the opacity, which increases with decreasing temperature, which again is the opposite of the behaviour of the opacity near the effective temperature of the Sun. We analyse the formation of dust above the cool magnetic spots, and suggest that the dust formation is facilitated by strong shocks, driven by stellar pulsations, which run through and around the spots. The presence of both the magnetic field and cooler temperatures makes dust formation easier as the shock passes above the spot. We review some observations supporting the proposed mechanism, and suggest further observations to check the model.

Key words: MHD – stars: AGB and post-AGB – circumstellar matter – stars: mass-loss – planetary nebulae: general.

1 INTRODUCTION

Several studies in the past have suggested that dust can form more easily above cool spots in evolved stars. Frank (1995) conducted a detailed study of dust formation above cool asymptotic giant branch (AGB) starspots, and showed that the mass-loss rate above the spots increases, though the outflow velocity does not change much. However, Frank does not discuss the source of the cool starspots. Schwarzschild (1975) suggested that cool regions in red giants are formed by very large convective elements. Polyakova (1984) suggests two antipodal active magnetic regions over which dust forms to explain the light and polarization variations in the M supergiant μ Cep. The spots rotate with the star and cause the observed light and polarization variations. She finds that a rotation period of about 20 yr and an activity cycle of about 2.5 yr fit the observations. Clayton, Whitney & Mattei (1993) suggest that the intensive dust formation close to the photosphere of R Coronae Borealis (RCB) stars can be facilitated by cool magnetic spots. In a recent paper, Soker (1998) proposed a scenario in which the axisymmetrical mass-loss during the high mass-loss rate phase at the end of the AGB, which is termed the superwind, results from dust formation above cool magnetic spots. He further argues that this scenario has the advantage that it can operate for very slowly rotating AGB and RCB stars, i.e., only $\sim 10^{-4}$ times the breakup velocity. This rotation velocity is 2–3 orders of magnitude smaller than what is required by models where rotation or the magnetic field have a dynamical role (Chevalier & Luo 1994; Dorfi & Höfner 1996; Ignace, Cassinelli & Bjorkman 1996; Garcia-Segura 1997). The scenario proposed by Soker (1998) and further explored in the present paper, applies only to elliptical planetary nebulae (PNs). The more extreme asymmetrical PNs, called bipolar (or butterfly) PNs, seem to require the presence of a close stellar binary companion to their progenitor, which influence the wind geometry more than any rotating single star mechanism (Soker 1997; Mastrodemos & Morris 1999).

The morphology of PNs and proto-PNs suggest that the transition to the highly non-spherical mass-loss episode at the end of the AGB is highly non-linear. By non-linear we mean that a small change in one or more of the properties of the AGB star leads to a very large change in the mass-loss rate and geometry. The mechanism of dust formation via the activity of a dynamo in the envelope of evolved stars is a highly non-linear process (Soker 1998). This dynamo is not required to form a strong magnetic field. A weak magnetic field is enough, as it will be enhanced inside cool spots by a factor of $\sim 10^4$ or more, by convective motion. In the Sun, for example, the magnetic field in cool spots is $\sim 10^3$ stronger than the average magnetic field. It cannot reach higher values near the photosphere, since then it greatly exceeds the ambient thermal pressure. Therefore, it is possible that even if the average magnetic field of the Sun were weaker, the intensity of the magnetic field would still reach the same value in cool spots.

Two points regarding the behaviour of the magnetic field should be noted here. First, the magnetic field is not a frozen-in field from the main-sequence phase, but is rather amplified by a dynamo

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process, which requires both turbulence and differential rotation. Giant stars are expected to rotate very slowly. However, the strong convection may compensate for the slow rotation (Soker 1998). Secondly, unlike solar-type stars, the interaction of the magnetic field with the wind will not slow the stellar rotation more than if there were no magnetic field. The reason is that, in the sun, the magnetic activity determines the mass-loss rate and geometry, and hence the magnetic field lines can channel the wind. In the sun, the average magnetic energy density is of the order of the kinetic energy density of the wind on the surface, or even larger. In AGB stars the ratio of the average magnetic energy to the kinetic energy density of the wind is $\sim 10^{-4}$ and below (Soker 1998). Therefore, unlike the situation in the sun, the magnetic field in AGB stars cannot bring the wind to corotate above the surface. In any case, we think that in most cases further spin-up of the evolving star occurs on the red giant branch or later on the AGB.

Convective influences on the magnetic field, dust formation and mass-loss rate as a result of dust, are all non-linear processes. For example, the density above the photosphere decreases exponentially with radius (Bedijn 1988; Bowen & Willson 1991). Therefore, if the temperature drops a little, dust formation will occur closer to the star where the density is much higher (Frank 1995). It has been suggested that the superwind results from this increase of the density scaleheight above the photosphere (Bedijn 1988; Bowen & Willson 1991). In Section 2 we examine some observations which support the formation of dust in cool magnetic stellar spots. Before doing that we would like to stress that we do not suggest that magnetic activity is the direct cause of the enhanced mass-loss rate near the equatorial plane. We still think that radiation pressure on the dust, the formation of which is facilitated by stellar pulsation, does the job. The magnetic field forms cool spots which further facilitate the formation of dust.

The photosphere of the cool spot is not at the same radius as the photosphere of the rest of the star (hereafter the stellar photosphere). In the sun, the photospheres of the cool spots are $\sim 2l_p$ deep in the envelope (Priest 1987, Section 1.4.2D), where l_p is the pressure scaleheight on the solar photosphere. This results from the lower density and temperature of the spot. Since the opacity *decreases* as temperature decreases, for conditions appropriate to the solar photosphere, the photosphere is at higher densities in the spot, which occurs deeper in the envelope. As we discuss in Section 3 below, the behaviour of the opacity is just the opposite in AGB stars. In these stars, the spot will be *above* the stellar photosphere. In Section 4 we discuss the formation of dust above magnetic cool spots, taking into account the magnetic field, and suggest observations to detect cool spots in AGB and RCB stars. We summarize in Section 5.

2 HINTS FROM RELATED SYSTEMS

2.1 AGB stars

Soker (1998) reviews several properties of PNs and AGB stars relevant to the cool magnetic spot model. The most relevant property that a theory for the formation of elliptical PNs should explain is the correlation between the onset of the superwind at the end of the AGB, and the transition to a more asymmetrical wind. In many elliptical PNs, the inner shell, which was formed from the superwind, deviates more from sphericity than the outer shell, which was formed from the regular slow wind (prior to the onset of the superwind). In extreme cases, the inner region is elliptical while the outer shell or halo is spherical (e.g. NGC 6826). In addition, most (~75 per cent) of the 18 spherical PNs (listed in Soker 1997, table 2) do not have a superwind, only an extended spherical halo. The correlation between the onset of the superwind and the onset of a more asymmetrical wind is not perfect, and in some cases both the inner and outer regions have a similar degree of asymmetry (e.g. NGC 7662). Soker (1998) and Soker & Harpaz (1999) suggest that magnetic activity may explain this correlation by becoming more pronounced at the end of the AGB phase, because of the decrease in the envelope density in the convective region (as a result of mass-loss), and the changes in the density and entropy profiles. Another supporting argument brought by Soker (1998) is the presence of magnetic fields in the atmospheres of some AGB stars. This is inferred from the detection of X-ray emission from a few M giants (Hünsch et al. 1998). Kemball & Diamond (1997) find a magnetic field at the locations of SiO maser emission, which form a ring around TX Cam at a radius of 4.8 au $\simeq 2R$, and mention the possibility that the mass-loss occurs in a preferred plane. They also suggest that 'the fine-scale features [of the Maser image] are consistent with local outflows, flares or prominences, perhaps coincident with regions in which localized mass-loss has taken place.'

We now add more supporting and motivating observations to those presented by Soker (1998), through a more careful examination of the stellar magnetic activity.

(1) From the sun we know that during most of the solar cycle, the cool spots are concentrated between the equator and latitudes $\pm 35°$ (e.g. Priest 1987, Section 1.4.2E). The model presented by Soker (1998) predicts, therefore, that during most of the AGB stellar cycle, a higher mass-loss rate will occur close to the equatorial plane. However, at the beginning of a new solar cycle, every ~11 yr, the cool spots are concentrated at two annular regions around latitudes $\sim \pm 30°$.

(2) In the sun there are at most several large spots at any given time. This means, for dust formation in AGB stars, that the mass-loss will be enhanced in specific directions, leading to the formation of dense clumps in the descendant PN (if spots survive for a long time).

(3) Another property of a stellar magnetic field is that the magnetic axis direction can change. If the magnetic axis and rotation axis are not aligned, then the magnetic axis direction will change during the stellar rotation. Another possibility is that the magnetic axis will change in a sporadic way, as has occurred several times for the magnetic field of the Earth.

There is no basic dynamo model with which to predict the length of the stellar cycle in AGB stars, the latitude at which spots appear at the beginning of such a cycle, or the change in the direction of the magnetic axis. In any case, some morphological features in PNs are consistent with an enhanced mass-loss rate in two annuli above and below the equator, and with a sporadic mass-loss rate above magnetic cool spots. Active annuli may form two dense rings, which might appear in projection as radial condensations in a symmetrical configuration, as in NGC 6894 (PNG 069.4-02.6; Manchado et al. 1996; Balick 1987). Some PNs show arcs and loops, e.g. A 72 (68PNG 059.7-18.7) and NGC 7094 (PNG 066.7-28.2) from Manchado et al. (1996), and He2-138 (PNG 320.1-09.6), M1-26 (PNG 358.9-00.7) and He2-131 (315.1-13.0) from Sahai & Trauger (1998), and long condensations extending from the shell toward the central star. Loops might be a result of the change in direction of the magnetic axis and of active annuli on the surface of the progenitor. Sahai & Trauger (1998) suggest that the change in direction of the symmetry axis,

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and the complicated structures in the inner regions of many PNs, may result from multiple substellar (mainly planets) companions which interact one after another with the AGB star. Although a substellar companion may be the source of the angular momentum required to operate the dynamo (Soker 1996, 1998), we think that the interaction of several large planets with different equatorial planes is very unlikely. We prefer sporadic behaviour of a stellar dynamo to explain these structures in elliptical PNs. (Well-defined jets in bipolar PNs cannot be explained by our model, and probably require stellar companions.) Large, long-lasting sporadic magnetic spots might form dense condensations, as in IC 4593 (PNG 025.3+40.8; Corradi et al. 1997), and A 30 (PNG 208.5+33.2; Manchado et al. 1996; Balick 1987). A30 has a large, almost spherical, halo, with optically bright, hydrogen-deficient blobs in the inner region (Jacoby & Ford 1983). The blobs, which are arranged in a more or less axisymmetrical shape, are thought to result from a late helium-shell flash. Soker (1998) suggests that, after the helium flash, the formation of dust occurred closer to the stellar surface and the process became more vulnerable to magnetic activity, resulting in the axisymmetrical mass-loss.

2.2 RCB stars

The RCB stars are rare hydrogen-deficient carbon-rich supergiants which undergo very spectacular declines in brightness of up to 8 mag at irregular intervals as dust forms along the line of sight (Clayton 1996). There are two major evolutionary models for the origin of RCB stars: the double degenerate and the final helium-shell flash (Iben, Tutukov & Yungelson 1996). The former involves the merger of two white dwarfs, and in the latter a white dwarf/evolved PN central star is blown up to supergiant size by a final helium flash. In the final flash model, there is a close relationship between RCB stars and PNs such as A30, discussed above. The connection between RCB stars and PNs has recently become stronger, since the central stars of three old PNs (Sakurai's Object, V605 Aql and FG Sge; Duerbeck & Benneti 1996; Clayton & De Marco 1997; Gonzalez et al. 1998) have had observed outbursts that transformed them from hot evolved central stars into cool giants with the spectral properties of an RCB star.

Wdowiak (1975) first suggested the possibility that dust in RCB stars forms over large convection cells which are cooler than the surrounding photosphere. Clayton et al. (1993)suggested that a magnetic activity cycle similar to the Solar Cycle could fit in well with the observed properties of RCB stars. It would provide a mechanism for a semi-periodic variation in dust production, could cause cool spots over which patchy dust clouds might form, and could be related to the chromospheric emission seen in these stars.

There is no direct observational evidence for a magnetic field in any RCB star. When in decline, RCB stars do exhibit an emission spectrum that is often referred to as 'chromospheric' although not all the emission lines typical to a chromosphere are seen. Lines associated with transition regions, such as C II $\lambda\,1335$, C III] $\lambda\,1909$ and C IV $\lambda\,1550$ are also seen (Clayton 1996; Lawson et al. 1999). These lines indicate temperatures of $\sim 10^5$ K. Models of the transition regions in other stars indicate that acoustic waves alone cannot provide enough energy to account for the radiation losses and a small magnetic field must be present (Jordan & Linsky 1987). [Another possibility is emission from gas excited by the passage of a pulsational shock. This phenomenon is seen in Miras (Bookbinder, Brugel & Brown 1989). However, the evidence from the RCB stars seems to indicate that the emission is present at all times, not just when a shock has passed (e.g. Lawson et al. 1999)]. No flares have been observed on an RCB star, although Y Mus does exhibit flickering in its light curve (Lawson et al. 1990; Lawson & Cottrell 1997). No X-rays have ever been detected. Photometric detection of starspots is difficult because of the presence of pulsations and dust formation events. There is no measurement of the rotation period of an RCB star. The effect of rotation is not measurable in existing high-resolution spectroscopic data (e.g. Pollard, Cottrell & Lawson 1994). Measurements place a lower limit of approximately one year on the rotational period. The pulsation periods of RCB stars lie in the range 40–100-d (Lawson et al. 1990). These are confirmed as pulsational variations by radial velocity measurements (Lawson & Cottrell 1997). Fourier analysis of RCB light curves do show significant low frequency ($\sim$200 d) contributions but they are attributed to couplings of higher frequency terms or the windowing effect of the observing seasons. RY Sgr has two periods seen in its light curve of 38 and 55-d (Lawson et al. 1990). However, only the 38-d period shows up in radial velocity measurements (Lawson & Cottrell 1997).

3 MAGNETIC COOL SPOTS

3.1 The position of the photosphere of the spot

Let us examine the structure of a vertical magnetic flux tube as is done for sunspots, following, e.g. Priest (1987; Section 8.4). There are many open questions regarding the formation and evolution of cool magnetic spots. However, it seems that there are two basic stages in their formation (Priest 1987; Section 8.6.1).

(i) The motion of convection cells concentrates magnetic flux to form a strong vertical magnetic field, which then suppresses the vertical convective heat transport, hence leading to a cool spot.

(ii) Material cools, because of the reduced heat transfer, and sinks inside the tube (Priest 1987, Section 8.6.1; Meyer et al. 1974). This further increases the magnetic field strength.

Soker & Harpaz (1999) argue that these processes become more efficient as the star evolves along the upper AGB and early post-AGB phase.

Since the magnetic pressure inside the vertical flux tubes below cool magnetic spots reaches values on the order of the convective pressure, it can inhibit heat transfer. If similar heat transfer reduction is produced whenever the magnetic field pressure is equal to the convective pressure, we can assume similar cooling of spots in the sun and on other stars. In any case, the biggest uncertainty in the model is the temperature of the cool spot, which is also the most important factor for dust formation. Keeping this in mind, we will make several simplifying assumptions in this section. Using the definition of the photosphere as the place where $\kappa l \rho_{\rm p} = 2/3$, where κ is the opacity, l the density scaleheight and $\rho_{\rm p}$ the density at the photosphere, the pressure at the photosphere is given by (e.g. Kippenhahn & Weigert 1990, Section 10.2)

$$P_{\rm p} = \frac{2}{3}\frac{GM}{R^2}\frac{1}{\kappa}, \tag{1}$$

where M is the stellar mass and R the photospheric radius. At the level of accuracy of our calculations, we can take the pressure and density scaleheight at the photosphere to be equal (we do not consider here the density inversion region below the photosphere of

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AGB stars; Harpaz 1984). The density at the photosphere is given by

$$\rho_p = \frac{2}{3} \frac{GM\mu m_H}{k} \frac{1}{R^2 \kappa T_p}, \tag{2}$$

where T_p is the photospheric temperature, k the Boltzmann constant, and μm_H the mean mass per particle.

A full treatment of the entire spot and the flux tube below it is too complicated, since the magnetic field lines curve outward near the photosphere, as is schematically represented in Fig. 1, and the magnetic tension must be considered (e.g. Priest 1987, Section 8.4.1), as must heat transfer. The central region of the flux tube is much simpler to treat, since the magnetic tension can be neglected there, because of the small curvature of the field lines, becoming zero on the centre. Our treatment below follows the one presented by Priest (1987, equations [8.43]– [8.47]), which is adequate for the entire flux tube below the photosphere, and near the symmetry axis of the tube at the photosphere. The approximations used become less accurate as we move away from the symmetry axis toward the boundary of the umbra, becoming very crude at the penumbra. As we shall see below, these approximations are quite good when applied to the sun. We are therefore confident that the simplified treatment gives reasonable estimates of the properties of cool spots on the surfaces of the evolved stars discussed in the present paper.

Let the subscript i denote quantities in the centre of the cool spot, and the subscript e quantities outside the spot, where the magnetic field can be neglected. Pressure balance between the spot and its surroundings reads

$$P_i + P_B = P_e, \tag{3}$$

where P_B is the magnetic pressure inside the cool spot. Derivation with respect to the radial coordinate gives

$$\frac{dP_i}{dr} = \frac{dP_e}{dr} - \frac{dP_B}{dr}. \tag{4}$$

As in the sun, we assume that the magnetic field lines inside the spot are vertical, and only near the photosphere do they open tangentially in order to reduce the magnetic pressure. The magnetic pressure deep in the envelope is of the same order as the thermal pressure. Near the photosphere the magnetic field has to open up in order for the magnetic pressure not to exceed the thermal pressure of its surroundings (e.g. Priest 1987, Section 8.4). We approximate the magnetic pressure gradient as

$$\frac{dP_B}{dr} = \frac{P_B - \alpha P_B}{d}, \tag{5}$$

where P_B is the magnetic pressure on the photosphere of the spot, and αP_B is the magnetic pressure at a radius equal to the surrounding photospheric (hereafter just photospheric) radius. d is the radial distance between the photosphere and the photosphere of the spot (see Fig. 1). In the sun, the spot is deep in the envelope.

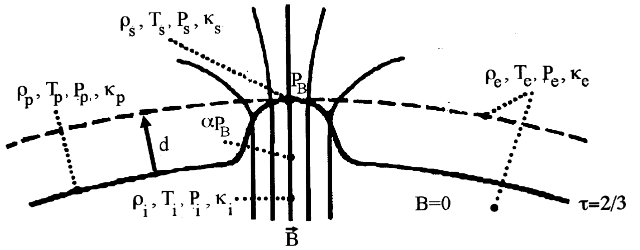

Figure 1. Schematic illustration of a cool magnetic spot on the surface of an AGB star (not to scale). See text for details.

In this case, d is negative and $\alpha < 1$. In AGB stars, we will find (below) that the spot photosphere is above the photosphere, so that $d > 0$ is positive and $\alpha > 1$. Since the vertical magnetic field lines do not exert radial force (e.g. Priest 1987, Section 8.4), the hydrostatic equilibrium within the spot does not include the magnetic pressure gradient

$$\frac{1}{\rho_i} \frac{dP_i}{dr} = \frac{1}{\rho_e} \frac{dP_e}{dr} = -g, \tag{6}$$

where $g = GM/R^2$ is the gravity in the photosphere. The magnetic field lines open-up near and above the photosphere of the spot, as is drawn schematically in Fig. 1, and is quantified in equation (5). This implies the presence of a magnetic tension. However, the magnetic tension is weak near the symmetry axis of the tube and spot, hence equations (3) and (6) are still valid there.

Substituting dP_i/dr from equation (4) into equation (6), and using equation (5) for dP_B/dr, gives

$$\frac{1}{\rho_i} \left(\frac{dP_e}{dr} - \frac{P_B - \alpha P_B}{d} \right) = \frac{1}{\rho_e} \frac{dP_e}{dr}. \tag{7}$$

In the photosphere $\rho_p \kappa_p l_p = 2/3$, while in the photosphere of the spot $\kappa_i l_i \rho_i = 2/3$. From the last two equations we find

$$\rho_i = \rho_p \frac{\kappa_p l_p}{\kappa_i l_i}. \tag{8}$$

We now use our approximation that the pressure scaleheight is equal to the density scaleheight. This is not a bad approximation when there is a steep pressure drop and a shallow temperature drop as in the photosphere. We can replace, to good accuracy, $(1/\rho_e)(dP_e/dr)$ by $(1/\rho_p)(dP_p/dr)$ on the right-hand side of equation (6). Multiplying and dividing the right-hand side (rhs) of equation (6) by P_p, and the same for the left-hand side with P_i, we find $T_i/l_i = T_p/l_p$. The density at the photosphere is given by $\rho_p = \rho_e e^{d/l_p}$, where ρ_e is the surrounding envelope density at the radius of the photosphere of the spot, and $l_p \equiv -P/(dP/dr)$ is the pressure scaleheight. Using the above expressions for l_i and ρ_p in equation (8), we find

$$\rho_i = \rho_e \left(\frac{\kappa_p T_p}{\kappa_i T_i} \right) e^{d/l_p}. \tag{9}$$

Since we are considering the photosphere of the spot, we will use the subscript s instead of i from now on. Dividing equation (7) by P_e, using the definition of the scaleheight $l_p \equiv -P/(dP/dr)$, and substituting for ρ_i from equation (9), gives after rearranging terms

$$\frac{\kappa_s T_s}{\kappa_p T_p} \left[1 + \frac{l_p}{d} \frac{P_B}{P_e} (1 - \alpha) \right] e^{-d/l_p} = 1. \tag{10}$$

3.2 The Sun

Let us examine the validity of the last equation for the Sun. For the solar photosphere $\rho_p \simeq 10^{-7} \mathrm{g cm^{-3}}$, $T_p = 5800$ K, gravity $g = 2.74 \times 10^4 \mathrm{cm\,s^{-2}}$, and $P = 1.2 \times 10^5 \mathrm{dyn\,cm^{-2}}$. From Alexander & Ferguson (1994) and the TOPbase data base (Cunto et al. 1993; Seaton et al. 1994) we find $\kappa \simeq 0.25 \mathrm{cm^2\,g^{-1}}$. The scaleheight is $l_p = 280$ km. For a typical large cool solar spot, we take $T_s \simeq 3700$ K (e.g. Priest 1987, Section 1.4). By using these opacity tables, we find the photospheric density and opacity to be $\rho_s \simeq 5 \times 10^{-7} \mathrm{g\,cm^{-3}}$, and $\kappa_s \simeq 0.05 \mathrm{cm^2\,g^{-1}}$. With these values, we solve equation (10). Note that since the opacity depends on the density as well as on the temperature, d is solved iteratively. In any case, the simplified treatment here does not require a sophisticated

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algorithm for the solution. When the pressure gradient is neglected, i.e., $\alpha = 1$, the solution is $d = -2l_p$, i.e., the spot is $\sim 2l_p \simeq 560$ km deep in the photosphere. With $\alpha \ll 1$ and $P_B \simeq P_e$, the solution is $d = -2.4l_p$, or a depth of ~ 670 km. These values are within the range of the depth of the spots in the Sun, $d \sim -500$–700 km, as inferred from the Wilson effect (e.g. Priest 1987, Section 1.4). This shows that equation (10) is a good approximation, at least for the Sun. The reason for the spots being deeper in the envelope is that for the typical parameters of the solar photosphere, opacity *decreases* as temperature decreases.

3.3 AGB stars

In AGB stars, the situation is the opposite of that in the Sun. From the data presented by Alexander & Ferguson (1994), we find that the opacity drops slightly to a minimum as the temperature drops to ~ 2700 from ~ 3000 K, but then sharply increases to a value $\gtrsim 50$ times higher at a temperature of $T \lesssim 2100$ K (all at a constant density). The higher opacity in the cool spots means that the density will be lower than in the rest of the photosphere. Lower density means a somewhat lower opacity, so that the real increase in opacity will be by a factor of $\lesssim 50$. Let us consider a specific example. From the definition of the pressure scaleheight, $l_p \equiv -P/(dP/dr) = P/(\rho g)$, we find (in the photosphere),

$$\frac{l_p}{R} \simeq 0.05\left(\frac{R}{300\,R_\odot}\right)\left(\frac{T_p}{3000\,K}\right)\left(\frac{M}{0.8\,M_\odot}\right)^{-1}$$
$$\simeq 0.05\left(\frac{T_p}{3000\,K}\right)^{-1}\left(\frac{M}{0.8\,M_\odot}\right)^{-1}\left(\frac{L}{6500\,L_\odot}\right)^{1/2}, \quad (11)$$

where the gravity is $g = GM/R^2$. We took the mean mass per particle to be $\mu m_H = 1m_H$, higher than for a fully ionized plasma since gas in an AGB star photosphere is partially recombined, and RCB stars are hydrogen deficient. The stellar mass is taken for a typical star on the AGB tip, with envelope mass of $0.2\,M_\odot$ and a core mass of $0.6\,M_\odot$. We use the scaleheight, radius, and temperature as in equation (11), to find the photospheric opacity and density. For the photosphere we get $\rho_p \simeq 10^{-9}$ g cm^{-3} and $\kappa_p \simeq 5\times10^{-4}$ cm^2 g^{-1}. Following the Sun, we take the cool spot to be at a temperature of $T_s = 2T_p/3 = 2000$ K. We find the density and opacity to be $\rho_s \simeq 5\times10^{-11}$ g cm^{-3} and $\kappa_s \simeq 1.3\times10^{-2}$ cm^2 g^{-1}, respectively. Solving equation (10) with these values and taking $\alpha = 1$, we obtain $d \simeq 2.85l_p$. Taking the magnetic pressure gradient into account, i.e., $\alpha > 1$, will reduce d. Here, $P_B < P_e$, since the pressures are evaluated at the location of the spot photosphere, $r = R + d$. It will be more convenient to write equation (10) in terms of the pressure ratio at the stellar photosphere rather than at the spot photosphere. We define $(P_B/P_e)_{phot}$ to be the ratio of the magnetic pressure inside the flux tube to the thermal pressure of the surroundings, where both pressures are taken at a radius equal to the stellar photosphere. P_B/P_e, on the other hand, is the ratio when both pressures are taken at a radius equal to the radius of the photosphere of the spot, and is given by

$$\left(\frac{P_B}{P_e}\right) = \left(\frac{P_B}{P_e}\right)_{phot}\frac{e^{d/l_p}}{\alpha}. \quad (12)$$

Rearranging terms in equation (10) gives

$$e^{-d/l_p} = \frac{\kappa_p T_p}{\kappa_s T_s} + \frac{l_p}{d}\left(\frac{P_B}{P_e}\right)_{phot}\left(1 - \frac{1}{\alpha}\right). \quad (13)$$

Under the condition that $\kappa_s \gg \kappa_p$, the first term on the rhs may become much smaller than the second term. For example, for $(P_B/P_e)_{phot} = 0.5$ and $\alpha = 2$, and with the other parameters as taken above, the solution of equation (13) is $d = 1.5l_p$. In this case, the second term on the rhs is 0.167, while the first term is 0.0577. We cannot make α much greater, since then d becomes smaller, and the pressure cannot drop by a large factor in such a short distance. Going back to neglect the pressure gradient, we examine other temperatures. At $T_s = 1600$ K, the opacity decreases (relative to 2000 K) to $\kappa_s \simeq 5\times10^{-3}$ cm^2 g^{-1}, and from equation (10) (and for $\alpha = 1$) $d = 1.7l_p$, while at $T_s = 2500$ K we find $\kappa_s \simeq 2\times10^{-3}$ cm^2 g^{-1}, and from equation (10) $d \simeq 1.2l_p$. We conclude that cool magnetic spots on the surfaces of AGB stars are protruding above the photosphere by 1.5–3 scaleheights. Cool spots at ~ 2500 K will probably have only a small influence, while at $T_s \simeq 1600$ K dust is already forming. The relevant temperature is ~ 2000 K, where the spots are $d \simeq 1.5 - 3l_p \sim 0.1 - 0.15R$ above the photosphere! In Section 4 we will discuss the implications of the protruding cool spots on dust formation and observations.

3.4 RCB stars

3.4.1 Cool RCB stars

Magnetic spots in cool RCB stars ($T_{eff} \simeq 5000$–7000 K) will be deeper than the surrounding photosphere, as in the Sun. Because of the composition of RCB stars (mainly helium), the opacities are lower than for solar composition. From equation (1) we see that the pressure will be higher than that of a solar-composition star with the same radius, luminosity and mass. As an example, consider an RCB star of surface temperature 7000 K, radius $70\,R_\odot$, hence luminosity of $L = 1.05\times10^4\,L_\odot$, and a mass of $0.6\,M_\odot$. From the table of the TOPbase opacity project (Cunto et al. 1993), and the scaleheight $l_p \simeq 0.03R$, by equation (11) (the mean weight per particle in RCB stars is larger than that assumed in equation (11), $>1m_H$, but to first order we can still use equation (11)) we find the opacity and density on the photosphere for these hydrogen-deficient stars ($X = 0,\ Z = 0.02$) to be $\kappa_p \simeq 1.3\times10^{-3}$ cm^2 g^{-1}, and $\rho_p \simeq 4\times10^{-9}$ g cm^{-3} (see also model atmospheres by Asplund et al. 1997). For a cool spot of $T_s = 2T_p/3 = 4700$ K, the opacity and density are $\kappa_s \simeq 6\times10^{-4}$ cm^2 g^{-1}, and $\rho_s \simeq 10^{-8}$ g cm^{-3}, respectively. From equation (10) we find the depth of the cool spot to be $d \simeq -1.2l_p \simeq -0.04R$. Taking the pressure gradient into account with $P_B = P_e$ and $\alpha \ll 1$, we find $d \simeq -1.7l_p \simeq -0.05R$. This is deeper than in the Sun, since in the Sun $(l_p/R_\odot) = 4\times10^{-4}$, while in cool RCB stars this ratio is two orders of magnitude higher. It will be interesting to conduct numerical simulations, similar to those of Woitke, Goeres & Sedlmayr (1996), but where the shock waves are traveling inside the 'pipe' of the deep, $d \simeq -0.05R$, magnetic spots on cool RCB stars. This, of course, is beyond the scope of the present paper. In Section 4.1 we suggest that formation of amorphous carbon dust occurs as the shock breaks out of the pipe on the surface of the star.

3.4.2 Hot RCB stars

For a temperature of $T_p = 18\,000$ K, luminosity of $L = 10^4\,L_\odot$, hence $R = 10\,R_\odot$, and a mass of $M = 0.6\,M_\odot$, we find from equation (11) $l_p \simeq 0.01R$. The photospheric opacity and density are $\kappa \simeq 0.4$ cm^2 g^{-1}, and $\rho_p \simeq 2\times10^{-10}$, respectively. Opacity

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tables for a hydrogen-deficient atmosphere at $T \gtrsim 15\,000$ show that the opacity depends very weakly (relative to the range of cool RCB stars) on temperature. In a small range near $\sim 20\,000$ K the opacity even increases a little as temperature decreases. Taking the opacity to be constant, and $T_s = (2/3) \times T_p$, as in the Sun, we find from equation (10) and for a small magnetic pressure gradient (in this case d is small, so we can take $\alpha \simeq 1$) that $d \simeq -0.4 l_p$. We see that the spot is well inside the photosphere, even when the opacity is taken to be constant. Below $\sim 15\,000$ K the opacity decreases steeply, and if the spot temperature is in this range, then the spot will be $\sim 1 - 2 l_p \simeq 0.01R$ inside the photosphere, much shallower than in cool RCB stars.

4 IMPLICATIONS

4.1 Dust formation

As a parcel of gas in the wind moves away from the cool spots, it starts to get more and more radiation from the hotter surface of the star surrounding the spot. Therefore, even if initially this parcel is much cooler than the rest of the gas in the wind, at some distance from the surface it will be at only a slightly lower temperature than the surrounding gas. In order to stay much cooler until dust forms, Frank (1995) finds that the cool spots should be very large; having radius of a few $\times 0.1R$, where R is the stellar radius. There is a problem in forming such large magnetic spots. This is because the strong magnetic field in cool spots is formed by concentrating a weak magnetic field. Magnetic flux conservation means that the area from which the weak magnetic field is concentrated to the spot is much larger than the area of the spot. This cannot be the case if the magnetic spot is as large as required by the calculation of Frank. The solution, we think, is that the dust forms very close to the cool spot, so that even small spots (but not too small) can form dust. We should stress again that the formation of dust above cool spots, as suggested here and by Soker (1998), is not intended to replace dust formation around the star at several stellar radii (as occurs in AGB stars). Our idea is that enhanced dust formation above cool spots increases the local mass-loss rate, and makes the overall mass-loss geometry less spherical.

AGB stars The temperature amplitude arising from the pulsation of Mira variables can be as high as ~ 15 per cent (e.g. Hoffmeister, Richter & Wenzel 1985). This means that a cool spot of temperature ~ 2000 K can cool to ~ 1700 K. The high density of the spot photosphere means that dust can already form at this, or at a slightly lower, temperature. Therefore it is quite possible that, when a large and cool magnetic spot forms, large quantities of dust are formed during the minimum temperature of each pulsation cycle.

RCB stars Such low temperatures are not attainable around cool and hot RCB stars even on cool spots. However, as described below, Woitke et al. (1996) show that for $\rho_s \sim 10^{-13}$ to $10^{-16}\,\mathrm{g\,cm^{-3}}$, conditions allow the condensation temperature for carbon to be reached as a shock passes through the atmosphere of the star. However, for higher densities, the adiabatic cooling is negligible during the re-expansion following the shock, so the temperature remains near the radiative equilibrium temperature. Therefore, the higher densities present inside the cool spot do not enhance dust formation in the Woitke scenario. The cooler temperatures and magnetic field, by enhancing adiabatic expansion (see below), may aid dust formation close to the spot where the densities are lower than inside the spot.

To present our proposed scenario for enhanced dust formation, in RCB and AGB stars, but in particular in hot RCB stars, we must first summarize the effects of shocks as calculated and discussed by Woitke et al. (1996). Woitke et al. study the effect of shock waves, excited by stellar pulsations, on the condensations of dust around cool RCB stars. They consider only the spherically symmetric case, with an effective temperature of $T_p = 7000$ K. They examine shocks, which begin to develop somewhere below the photosphere, as they run out to several stellar radii. The shock velocities in their calculations were 20 and $50\,\mathrm{km\,s^{-1}}$. Somewhere outside the photosphere, at radius of $\sim 2R$, the density is in the right range for the following cycle to occur. (*i*) As the shock passes through the gas, it compresses the gas by a factor of ~ 6–10, and heats it by a factor of ~ 3–10. The compression and heating factors depend mainly on the shock velocity. (ii) As a result of its higher temperature, and to a lesser degree because of its higher density, the gas cools very quickly to its radiative equilibrium temperature. This equilibrium is with the radiation from the photosphere. (iii) The compressed gas re-expands and its density drops by more than an order of magnitude. This results in a large adiabatic cooling, which may bring the gas to below the dust-condensation temperature. The decrease in density and hence the adiabatic cooling becomes more pronounced as the shock velocity increases. In the Woitke et al. calculations, a $50\,\mathrm{km\,s^{-1}}$ shock results in dust formation, while for a $20\,\mathrm{km\,s^{-1}}$ shock, no dust forms.

Let us examine what happens during this three-stage cycle for gas above a cool magnetic spot. The pressure equilibrium above the photosphere is given by equation (3), i.e., the thermal pressure above the spot plus its magnetic pressure equals the thermal pressure of the surroundings (where the magnetic pressure is very small). (i) As a strong shock moving radially outward passes through a region, it compresses the gas by a factor >4, and heats it. The thermal pressure in the calculations of Woitke et al. (1996) increases by a factor of $\sim 10^2$. Since the magnetic field lines near the centre of the spots are radial (e.g. Priest 1987), the magnetic pressure does not increase behind the shock. Therefore, the surrounding post-shock pressure exceeds that of the region above the spots. The surrounding post-shock pressure compresses the region above the spot in the transverse direction, increasing both the thermal and magnetic pressure there, but the magnetic field is still smaller than is the thermal pressure. Therefore, the region above the spot is compressed by a larger factor than is the surrounding medium. This increases the efficiency of the mechanism studied by Woitke et al. Both regions, above the spot and the surroundings, reach similar thermal states since the magnetic pressure is small. (ii) Because of the high density, the gas in the two regions cools very fast to its radiative equilibrium temperature. However, above the spot the temperature will be lower. (iii) The compressed gas re-expands and its density drops by more than an order of magnitude. Because of the cooling and the re-expansion, mainly in the radial direction, the thermal pressure drops and the magnetic pressure above the spot becomes an important, or even the dominant, pressure. The magnetic field pressure results in a transverse expansion of the magnetic field lines. Since the gas is partially ionized, it will be practically frozen-in to the magnetic field lines, and the gas above the spot will expand transversely as well. The net result is that during the adiabatic cooling stage, the gas above the spot will re-expand by a larger factor, and hence will reach lower temperature. To summarize, cool magnetic spots have two factors which ease dust formation. First the temperature is lower, and secondly, the magnetic field increases both the total compression and the total

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re-expansion, and hence the adiabatic cooling, of the region above the spot. Lowering the temperature and density of the spot and the gas above it makes the dust formation mechanism studied by Woitke et al. effective closer to the stellar surface.

4.2 Observations

Clayton et al. (1997) found that in a deep decline of R CrB, the position angle of the continuum polarization was almost flat from 1 μm to 7000 Å but then changed rapidly, rotating by $\sim 60°$ between 7000 and 4000 Å. This behaviour is strikingly similar to that produced in post-AGB stars having an obscuring torus and bipolar lobes of dust. These new data strengthen the earlier suggestion that there is a preferred direction to the dust ejections in R CrB (Clayton et al. 1995). Dust ejections seem to occur predominantly along two roughly orthogonal directions consistent with a bipolar geometry. Another example of asymmetrical mass-loss from RCB stars is the apparent bipolar nebulosity observed around UW Cen (Pollacco et al. 1991). However, Clayton et al. (1999) find that the shape of the nebula changes with time as a result of changes in the illumination from the star. More observations are planned to detect and map the morphology of shells around RCB stars.

Starspots have been detected and mapped on a number of stars using techniques which combine photometry and spectroscopy (Vogt & Penrod 1983; Strassmeier 1988 and references therein). The Doppler imaging technique uses spectra of sufficient resolution to resolve individual stellar lines into several velocity bins. Because RCB stars likely rotate so slowly, extremely high spectral resolution would be required for Doppler imaging. However, accurate long-term photometric observations can be used to test for the presence of spots. The problems of confusion with pulsations and dust formation remain. The predicted RCB starspots will lie below the photosphere like those on the Sun and should be distinguishable from spots at the level of, or higher than, the stellar photosphere as we predict for AGB stars. As a result of the Wilson effect, the spots will be vignetted when near the stellar limb affecting the photometric behaviour of the star (Priest 1987).

The main problem of observing cool spots on these evolved stars is that when the spot is large and long-lived, we predict enhanced dust formation, which complicates the observation. In addition, these stars rotate very slowly, so the rotation period is likely to be longer than the lifetime of a magnetic cool spot. This means that photometric variations arising from rotation are very hard to detect. Therefore, the detection of cool spots is very tricky. In RCB stars a careful observation should be made before a deep decline, looking for photometric characteristics of a large cool region (of course, we will know we observed at the right time only after the decline). The spot will form on a dynamical time-scale, which for RCB stars is $\sim$1–2 months. Pulsation, as stated above, will complicate things considerably. In any case, broad-band photometry of an RCB star obtained over a few months before a decline should be carefully compared with observations of the same time span in quiet times.

In AGB stars the situation is much more complicated. In addition to dust formation above cool spots, the star forms large quantities of dust further out because of the large amplitude stellar pulsations and the cool photosphere. These stars tend to be obscured by dust. We suggest the following type of observations. The target stars should be on the upper AGB, preferentially carbon stars, but before dust obscuration. At this stage, magnetic activity starts to become significant (Soker & Harpaz 1999), and the cool spots are expected to live for a few weeks to a few months. Continuous broad-band photometry (i.e. VRI) should be made for a complete pulsation cycle, about a year. For both the RCB and AGB stars, a spot computer model will attempt to fit the light variations in various bands to multiple spots on the surface of the star (Strassmeier 1988). The different points on the surface inside and outside of spots will be assigned different temperatures. The flux is then integrated over the visible hemisphere of the star and then compared to the photometric observations in different bands. Good fits can be obtained using this method but the results are not unique unless combined with Doppler imaging. In parallel, a search for magnetic fields in, e.g. SiO masers, should be made.

A protruding cool magnetic spot (Section 3.3), when at an angle of $\sim 90°$ to the line of sight, will cause the AGB star to appear asymmetrical. Speckle interferometry can be used to study such stars to detect deviations from symmetry. Karovska et al. (1991) mention several possibilities for the asymmetry they detect in Mira, one of which is a large convective spot (Schwarzschild 1975). We would like to add to their list a large protruding magnetic spot, as one of the possibilities of causing deviations from sphericity.

5 SUMMARY

Our main goals and results can be summarized as follows:

(1) Properties of cool magnetic spots as known from the Sun can naturally explain many properties of mass-loss from AGB and RCB stars. The assumption that we have made here is that magnetic dynamo activity occurs in these evolved stars even when they rotate very slowly, $\sim 10^{-4}$ times their equatorial Keplerian velocity (Soker 1998).

(2) We calculate the position of the photosphere of the spots. In AGB stars the spots protrude from the photosphere, while they are deeper in the envelope of RCB stars.

(3) Using the mechanism proposed by Woitke et al. (1996), and the results of Frank (1995), we suggest that the lower temperature and the magnetic field above the spot facilitate dust formation closer to the stellar surface, after the passage of a shock wave driven by the stellar pulsation.

(4) We propose observations that can be made to look for the presence of cool magnetic spots on AGB and RCB stars. These include long-term photometric monitoring in several broad-band filters, with a temporal resolution of days, and speckle interferometry of AGB stars.

(5) Future calculations should combine the work of Frank (1995); Woitke et al. (1996)with a magnetic field above the spot. We need 2D or, even better, 3D simulations of shock waves propagating from the cool spot and around it, including the magnetic pressure above the spot.

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