Aerosols in Astrophysics

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ABSTRACT:

Solid phase material exists in low density astrophysical environments, from stellar atmospheres to interstellar clouds, from current times to early phases of the universe. We consider the origin, composition and evolution of solid phase materials in the particular case of stellar outer atmospheres, as representative of many conditions. Also considered are the dynamics and interactions in circumstellar and galactic environments. Finally, new observational prospects for spectroscopy, polarimetry and interferometry are discussed.

1.0 INTRODUCTION

Solid phase material can be found nearly everywhere in space. In the astronomical literature, these tiny solids are referred to as "dust" and/or "grains" in discussions of the most important opacity source at wavelengths longer than the Lyman limit for ionizing hydrogen (91 nanometers). These solids play key roles in molecular clouds and star formation – enabling cooling, shielding from radiation and energetic particles, and forming the basis for planetessimal formation in primitive solar systems. The spectral energy distributions of all of these astronomical objects are strongly modified by solid particles, which Carl Sagan once characterized as having the size and average composition of bacteria. In this review, we focus on the role that solids play in the most evolved stars. As these stars complete their cycle of existence, there is a wholesale return of modified material back to the interstellar medium, affecting the next generation of star and planet formation.

Evolved stars are characterized by surface temperatures low enough to allow molecules and solid-phase particles to exist in their atmospheres. In contrast to the nearly 6000K surface temperature of the Sun, the kinetic temperatures of evolved stars may range between 2000K near their "surfaces" to a few hundred K in their circumstellar envelopes [CSE] at a few stellar radii distance. Time-dependent phase transitions from ionized plasma to cold, solid state are observed, spectroscopically, to exist.

Some terminology may be helpful for the reader not already acquainted with stellar evolution. Solar mass stars are predicted to leave the hydrogen-fusing "main sequence" after approximately ten billion years, and progress through a rapid series of internal changes during what is known as the red giant and asymptotic giant branch [RGB, AGB] phases, lasting one percent of the main sequence lifetime. These internal changes are driven by interior thermodynamics, as helium fusion is initiated and exhausted as a primary energy source, past the main sequence. The important phenomenon during these latter phases is the high rate of evaporation (mass loss) of the outer layers, which during peak times can rival the internal evolutionary timescales. The outflows are estimated to alter the chemistry of the interstellar medium and ultimately, the galaxy. The evaporation rate is modulated by the quantity and composition of molecular and solid material in the outflow. Hence, understanding the role of solids in circumstellar environments is key to correctly predicting the evolutionary paths of stars of diverse initial masses and compositions.

1.1 Aerosols

Most studies treat solids and the surrounding gas as a two fluid system. While this has been useful in advancing the subject, modern computing power may allow us to consider the system in combination as an "aerosol". An aerosol is defined in its simplest form as a collection of solid or liquid particles suspended in a gas (Hinds, 1999). Aerosols are two phase systems, consisting of the particles and gas in which they are suspended (cf . Seinfeld and Pandis 1998). This definition admits a range of sizes from molecular clusters (tens of nanometers) to solids (micron-sized), and can include neutrals as well as ions – exactly the mix found in circumstellar environments (CSE). Terrestrial atmospheric densities and temperatures range from 10^{-3} g cm^{-3} ($10^{19.4}$ cm^{-3}, 288K) at the surface, to roughly six orders of magnitude less density in the upper stratosphere (~200K). While the temperatures resemble circumstellar ones, terrestrial densities are orders of magnitude larger. Micron sized terrestrial aerosols float in a molecular nitrogen and oxygen gas, while circumstellar aerosols form and move in a mostly hydrogen gas medium. Therefore, it is timely to review recent progress in astrophysical descriptions of CSE, along with advances in terrestrial atmospheric aerosol chemistry and rarified gas dynamical theory and experiment, applied to an astrophysical context.

1.2 Mass Loss Mechanisms

It long been known that red giant and supergiant stars are losing mass at high rates in the latter stages of life in an observable expansion called the stellar wind. Stellar wind theories can be grouped into four main categories: thermal-driven, radiation-driven, wave-driven, and shock-driven (pulsation, radiation and dust). An excellent summary of the relevant physics was presented by Holzer and MacGregor (1985).

Two of the most important parameters describing a stellar wind are derivable from observation: the mass loss rate [the amount of mass lost by the star per unit time] and the terminal velocity [the velocity of the stellar wind at a large distance from the star]. Stellar mass loss rates vary from present solar wind levels (10^{-14} solar masses per year) to AGB and post-AGB "super-wind" phases (up to 10^{-4} solar masses per year), deduced from spectroscopically observed density and velocity. The spectral lines from stellar winds can often be distinguished from the photospheric lines due to their large width or Doppler shift produced by the outflowing motion of the gas in the wind. Wind lines can appear in emission, in absorption, or as a combination of the two [P Cygni profile], where observable absorption and emission lines show a Doppler shift due to the outflow, even with relatively small mass loss rates. Stellar wind speeds range from 10-20 km per second for an AGB star, to ~500 km per second for the solar wind near earth, to over 3,000 km per second (1% of the speed of light!) for an early type star, such as an O6 star. Although the velocity structure of the wind varies as it progresses out from the photosphere, for a typical AGB wind velocity, the crossing time for a wind traveling out 1000 AU from the star would be about 50 years.

Stellar winds require heat input or momentum input to become transonic, varying from subsonic (typically, a few km/sec) to supersonic with height. The energy per unit mass of an atmosphere, which is gravitationally bound, must be negative. The energy of an outflow, which escapes the gravitational potential well of the star, is positive at large distances. This requires that energy must be added to the gas in order for it to escape. The energy can be added in the form of heat input or work done by an outward directed force (momentum input). Four general *wind driving mechanisms* have been discussed in detail (cf. Holzer & MacGregor 1985): thermally-driven, line-driven, wave-driven and shock-driven winds.

(a) The concept of thermally-driven winds was developed in the early 1960's mainly by Eugene Parker. In this model for the wind, the only important outward force exerted on the expanding atmosphere would be the thermal pressure gradient. Thermally driven winds require high (coronal) temperatures, and exhibit much larger radiative fluxes, especially in the ultraviolet and extreme-ultraviolet. Unlike the sun, red giant and supergiant stars do not have hot coronae, effectively ruling out this mechanism.

(b) For line-radiation driven winds, the electromagnetic radiation field of a star provides a reservoir of momentum that can be used to drive a stellar wind. This mechanism works when there is a coupling of the radiation field to the gas/dust in the atmosphere. Radiation-driven winds work well for hot stars when the atmosphere exhibits many strong UV resonance lines and the radiative flux is substantial in the ultraviolet. The coupling comes from the stellar radiation and the atmospheric opacity. Stellar radiation for cool stars peaks in the red or near-infrared, and the strong resonance lines of the atoms occur in the visible and ultraviolet. Therefore, this mechanism acting alone can be ruled out for red giant and supergiant stars. Although, for the most luminous and coolest AGB stars, where the dust forms close to the photosphere, radiation force on the dust grains might drive massive outflows from the star.

(c) Wave-driven winds involve the transport of a mechanical energy flux through the stellar atmosphere and takes into account only small amplitude waves for energy transport, including weak shock waves. When a magnetic field is present the small amplitude waves will either be compressive or non-compressive, corresponding to acoustic or Alfven waves. However, the compressive waves tend to steepen very rapidly into weak shocks and are dissipated within a few pressure scale-heights of the base of the atmosphere. Therefore, although acoustic waves can levitate material to a small height in the atmosphere they are not strong enough to lift a massive wind out of the stars' gravitational well. With sufficient magnetic field strength relative to the thermal energy, Alfven waves show promise for driving outflows, particularly in the solar case. Questions related to energy dissipation in these waves remain unresolved.

(d) Shock-driven winds (combination of pulsational ‘levitation’ and outward radiation forces on dust) arise from the coupling of the stellar radiation field to a sufficiently dusty atmosphere and CSE already expanded by the effect of pulsations. Variable stars, such as the ones of interest in this study, exhibit somewhat regular pulsations that produce large-amplitude shock waves propagating outward through the photosphere and into the CSE. This allows for the stellar material to be lifted to sufficient height where dust will form and where the escape velocity is substantially lowered. Often these winds are termed “dust-driven”, but one should retain an open mind to the idea of “wind-driven” dust in these systems.

1.3 Stellar Winds in Evolved Stars

Among AGB stars, there is a subset known as “Mira” variables, named after the prototype, omicon (Mira) Ceti. These are known to execute periodic, several magnitude variation due to large-amplitude radial pulsations, on timescales of 100 to 1000 days. Whether the usual oscillation mode is the fundamental or first overtone remains unresolved, despite strong opinions expressed on the subject. Dynamical structure models by Bowen (1988) found that fundamental-mode pulsations better matched actual observations, because the models driven at their overtone periods showed to have different properties, including shocks of smaller amplitude occurring at smaller radius and larger density than shocks in fundamental-mode.

Dust driven winds only occur in the very restricted portion of the HR diagram that contains the cool, high luminosity red supergiant and AGB stars (including the Mira type). The effective (surface) temperatures of these stars range from 2000 to 3000 K and the luminosities are 10^4 times solar for the AGB and 10^5 times solar for the red supergiant stars. The low CSE temperatures allow for formation and growth of molecules and clusters of molecules to occur. The temperature and radiation field determine the altitude above the photosphere where molecular formation or “condensation” of particles begins, in competition with the decreasing density of the gas with increasing distance from the star. It is the density of the condensation radius that determines how many solid phase materials form and whether there is sufficient momentum coupling between the gas and particles to sustain an outflow. If the value of the density is too low there will be too few collisions between gas atoms to form the initial molecules, and conditions supportive of a dust-driven stellar wind will not be generated. The dynamics of this are the subject of a later section of this review.

Dust condensation begins to occur at temperatures as low as 1500K for aluminum oxides, and less than 1000K for silicon monoxide in oxygen-rich stellar atmospheres and amorphous carbon dust in carbon-rich stellar atmospheres. Whether a stellar atmosphere is oxygen or carbon rich is a strong function of stellar evolutionary state. The interior production and dredge up of carbon contaminates the atmosphere of stars where oxygen may have been the slightly more abundant, locking up the free oxygen in carbon monoxide molecules. These temperatures are not significantly below the photospheric levels for cool stars, and the formation of molecules and post shock cooling offer means to reach condensation temperatures while still near the denser stellar photosphere (cf. Muchmore, Nuth and Stencel 1987).

The temperature of newly formed molecular clusters is mainly determined by the equilibrium between the heating due to absorption of stellar photons, and the cooling by thermal emission. Therefore, the particulate temperature depends on the opacity of the cluster material, and on the ambient radiation field, and will roughly decrease with distance from the star if the CSE is optically thin. The innermost radius where particulates can survive ranges from 1.1 to a few stellar radii for stars with effective temperatures in the range 2200 to 3000 K. Interestingly, highly variable SiO masers are observed using radio astronomy methods, precisely in this domain. Once formed, these particles can be quickly accelerated outward due to their large opacity (see following sections). In dust driven winds, the sonic point and critical point both occur at about this condensation radius. Therefore, the mass loss rate is determined by the density at the condensation radius.

1.4 Scope of this Review

Whereas the topic is diverse and touches upon many fields in astrophysics, from cometary origins to galactic evolution, we limit consideration to optically thin, O-rich dust shells, in the interest of providing a focus. The related issues of carbon-rich circumstellar chemistry are discussed elsewhere. The purpose of this review is to provide access to the expanding discussion of silicate chemistry among evolved stars during the current explosion of data taking capabilities in the infrared and radio parts of the spectrum. The interested reader can follow the numerous references provided in each of the papers we cite. In section Two, we consider the origin, composition and evolution of solid phase materials, and laboratory analogues. Section Three discusses the dynamics and interactions in circumstellar and galactic environments. Section Four describes some of the observational prospects for spectroscopy, polarimetry and interferometry.

2. CIRCUMSTELLAR AEROSOLS

2.1 Recent Infrared Spectroscopy

Overview: In addition to ground-based mid-infrared spectroscopy, hampered by terrestrial atmospheric absorptions in the 1 to 20 micron region, two important surveys from space have been completed: the Infrared Astronomical Satellite (IRAS Low Resolution Spectrometer, Olnon et al. 1983) and the Infrared Space Explorer (ISO, 1995). Key among the findings has been the utility for diagnostic study of physical conditions using the following spectroscopic features (cf. Spoon et al. 2002). Cold molecular gas component – CO and SiO bandheads at 2.29 and 4.67, and 4.0 and 8.0 microns respectively (cf. Winters et al. 2000; Arlinger 2000), plus rotational lines of H2 between 2 and 28 microns (cf. van den Ancker et al. 2000), 3.0 and 5.5-8 micron water ice features, and the 4.26 micron carbon dioxide ice feature. The ice feature profiles are highly temperature sensitive and when irradiated exhibit signs of ice mantle processing in the "XCN ice feature at 4.62 microns and the 4.67 micron CO ice feature as well. The Poly-cyclic Aromatic Hydrocarbon features [PAH] appearing at 3.3, 6.2, 7.7, 8.6, 11.3 and 12.8 microns, are highly sensitive to the irradiation from nearby hot star sources (as in photo-dissociation regions, PDRs). But, it is the stretch mode of the Si-O bond that gives rise to the strongest feature, centered at 9.7 microns, but appearing over the 8 to 12 micron interval depending on degree of crystallinity, etc. Related silicate features have been detected at 9.7 and 18.5 micron (amorphous silicates) and 11.2, 27.5, 33.5, 35.8 and longer wavelengths (crystalline silicates). In carbon stars, graphitic and crystalline forms are indicated.

Grain composition: In a series of papers, Molster et al. (2002) report Infrared Space Observatory (ISO) short and long wavelength spectrometer (SWS, LWS) observations of crystalline silicate dust in a diverse sample of 17 evolved stars, including AGB, post-AGB, PN and RSG and hot star prototypes, which contrast quasi-spherical outflow versus disk-like circumstellar geometries. They defined seven wavelength regions with silicate "complexes" of subfeatures, near 10, 18, 23, 28, 33, 40 and 60 microns. Most of the bands were identified with forsterite

(Mg_2SiO_4; the Mg-rich crystalline olivine) and enstatite ($MgSiO_3$; the Mg-rich crystalline pyroxene). For a general discussion of the mineralogy, see, e.g., Jaeger et al. 1998, and Speck et al. (2000). About 20 percent of the bands lacked identification. The broad feature in the 10 micron complex is thought to originate from amorphous silicates, with sharper features from the crystalline forms, and indicative of larger particle sizes or composition differences. The outflow sources have a lower abundance of crystalline silicates, but a higher abundance of crystalline H_2O-ices (43 and 62 micron features) which avoid UV processing into amorphous forms due to clumping. On average, they concluded, crystalline silicates are colder (<100K) than amorphous silicates (>100-300K).

Tielens, et al. (1997) provide a discussion of these features in the context of mineralogical condensation sequences. The narrowness of spectral peaks atop a broad feature ascribed to amorphous silicates, implies the existence of crystalline carriers (Koike et al. 1993). Tielens et al. suggest initial formation of corundum (Al_2O_3) at temperatues below 1700K, which reacts with SiO, Ca and Mg to form spinel (Mg Al_2O_4) and eventually diopsides (CaMg Si_2O_6). Most of the silicates nucleate and condense as forsterites (Mg_2SiO_4), the Mg-rich end member of the olivine family. Then, excess SiO converts forsterite into enstaties (pyroxene, $MgSiO_3$), with the enstatite/forsterite ratio increasing with decreasing temperature. The presence of individual species in any given stellar spectrum is indicative of “freeze out” whereby the condensation sequence is interrupted by lack of density and temperature to sustain same, and thereby help interpret assorted spectral sequences (cf. Stencel et al. 1990 and others). An important aspect of these condensation scenarios involves the question of the low incidence of elemental iron involvement with silicates, such as fayalite (Fe_2SiO_4): kinetic freeze-out; preferential condensation as metallic iron, or, the preponderance of amorphous forms of silicate in circumstellar outflows. The latter scenario would be consistent with preferential loss of tiny amorphous grains, as predicted by dynamical models (see next section), and observed in the cases of silicate-rich shells around some carbon stars. Interestingly, even the planet Mercury shows less spectroscopic FeO than other terrestrial planets, suggesting the difficulty of binding Fe into Mg-silicates.

Grain sizes: The consistent use of Mie theory for lack of a better approximation insures that well-developed dust shells will be evaluated to have grain sizes in the domain of the wavelength of observation. Molster et al. (1999) assume spherical grains, an interstellar (MRN) power-law size distribution and use Mie theory to calculate the optical properties of the grain population. This approach allows for the calculation of emission for arbitrarily larger grains, which are abundant in the shell of the high luminosity source, AFGL 4106. They conclude grain sizes of 0.4 to 6 microns are the most common, with mass fractions of 65% amorphous olivines, 15% corundum, 10% enstatite, 5% each water ice and forsterite and essentially no FeO. Sogawa & Kozasa (1999) report that a homogeneous condensation of corundum grains, the accretion of silicate, starting slightly inside the so-called sonic point, results in heterogeneous grains consisting of a corundum core and silicate mantle. In their model, homogenous silicate grains begin in the 1.5-6 nanometer (nm) size range, and heterogeneous grains grow from 0.15 to 0.4 microns in size. Fabian et al. (2001) state that observed ISO band positions (peaks at

9.4 and 11.4 microns) are better reproduced by a wide distribution of ellipsoidal grain shapes, whereas the 9.8 micron peak is indicative of spherical grains. Difference in spectra may then reflect initial formation as amorphous spheroids and subsequent annealing into elongated crystalline particles. On a still larger scale, in a series of papers, Jura and colleagues have used infrared and submillimeter detections of high luminosity, post AGB objects to infer grain sizes, based on the assumption of extrapolated extinction coefficients and other simplifying assumptions. The scaling laws ($a = 3L_*/16\pi G M_* c\ \rho$) and observed radio line widths argue for the existence of orbiting reservoirs of materials with particles sizes as large as 5 millimeters, depending on whether the material obeys opacity laws that vary with frequency to the 0.6 power in the Rayleigh-Jeans limit. Ring and disk masses as large as one solar mass were inferred (cf. Jura et al. 2000). Hence, aerosol sizes from nanometer to millimeter in circumstellar outflows have been estimated.

2.2 Recent Microwave Maser Mapping

One of the key diagnostics of the dynamics of the CSE is the maser emission from SiO molecules (v=1, J=1-0 and J=2-1) detected at 43 and 86 GHz. Recently, improvements in polarization calibration at high frequencies and total intensity multi-dish interferometric observations have demonstrated the SiO masers spots are confined to a narrow ring like morphology (tangentially amplified, cf. Diamond et al. 1994) around many late type stars, indicating orderly motions and systematic velocity distributions in the 1 to few stellar radius domain. As the SiO molecule is nonparamagnetic, if exhibits significant linear polarization in the presence of a magnetic field, enabling determination of magnetic field strength in this key region. Kemball and Diamond (1997) deduced a line of sight field strength in the Mira TX Cam of 5-10 gauss. Vlemmings et al. 2002 have compiled this and related magnetic field strength determinations for related stars using SiO as well as H2O and OH masers at correspondingly greater distances to indicate an inverse square law like variation of magnetic field strength with distance around evolved stars, and that the magnetic pressure dominates the thermal pressure by a factor of more than an order of magnitude. This clearly indicates how the dynamics can be affected by the magnetic field.

2.3 Recent Laboratory Work

Whereas several groups have been pursuing laboratory studies of circumstellar aerosols, recent work by Hallenbeck et al. (1998) and Reitmeijer et al. (2002) appear to offer the most interesting prospects in connecting astronomical and synthetic properties. In both sets of experiments, amorphous magnesium silicate smokes were prepared by vapor phase condensation and annealed in vacuum, then monitored by IR spectroscopy with respect to annealing time and temperature. Hallenbeck et al. report wavelength dependent shifts, moving from 9.3 toward 11.2 microns, in silicates (Si-O stretch modes) as the experiment progressed from fully amorphous to increasingly crystalline, suggesting a natural pause ("stall") between the initially chaotic condensate and subsequently more ordered crystalline forms. The stall represents a stage in development of ordered material, but chemistry (oxidation state) is suspended in favor of internal mobility of components (polymerization). Noteably, they report the appearance of a peak near 11.3 microns, which is cited as a crystalline feature in cometary and astronomical spectra (cf. Molster et al., above), but appears in the lab well before significant degree of crystallinity is developed. This suggests the prior interpretation of astronomical spectra could be naïve. Hallenbeck et al. also studies iron silicate smokes and found these to evolve orders of magnitude more slowly.

The followup investigation reported by Rietmeijer et al. (2002) traces mineralogical and chemical properties of the magnesium silicate lab samples, particularly an unanticipated size dependence of the petrological development of amorphous phases as related to spectral changes. Specifically, grains smaller than 20 nm remained amorphous throughout the entire thermal annealing experiment. Solid state changes only seemed to occur after smaller grains were fused and chemically homogenized. Unstable nanocrystals of independent SiO_4 tetrahedra (neosilicates: forsterite and tridymite) were present during stall phases until sufficient quantity of magnesiosilicate sheet structures grew that then supported development of chains of tetrahedral nucleation (inosilicates, including enstatite), in domains larger than 20 nm. They were able to fit the 9-11 micron spectral evolution with seven subcomponent profiles, with narrowing and sharpening of peaks observed as annealing progressed. Can evidence for analogous behavior, including "stall" phases be seen in CSE? Increasingly, astronomical observations are beginning to sense the presence in such environments, of a bimodal distribution of particle sizes: small "hot" grains smaller than 50 nm, and larger sub-mm sized ones. This is a key point as we next begin our discussion of the dynamics of these particles in aerosol states.

3.0 CIRCUMSTELLAR AEROSOL DYNAMICS

Once formed, the aerosol particles can behave independently from the gas in the stellar atmosphere, depending on the precise conditions. There seems to be emerging consensus that tiny grains will be decoupled from the gas and accelerated into the circumstellar envelope (MacGregor and Stencel, 1992; Liberatore et al. 2001, Elitzer and Ivezic 2001). Examining prior work by R. Gilman and by N. Berruyer, for under conditions typical of the circumstellar envelopes of oxygen-rich red giant stars, MacGregor and Stencel (1992) solved the aerosol equation of motion and found that particles with radii smaller than 0.05 micron decouple from the ambient gas near the base of the outflow. Liberatore et al. (2001) concur that electrostatic drag is many orders of magnitude less important than collisional drag in outflows of this type, and describe two dynamical regimes: a boundary layer where the particles are strongly accelerated relative to the gas, and an outer regime where the two are strongly coupled, but do not compute details of the former. They admit the decoupling will strongly influence grain growth. Simis et al. 2001 demonstrate that gas-particle drift is an essential feature in time dependent hydrodyamical solutions to explain the creation of quasi-periodic shells among highly evolved stars. However, Elitzur and Ivezic (2001) proclaim to have fully solved the dusty wind problem, at least from the layers outward after dust formation is completed. Once radiative forces accelerate the particles relative to the gas, the complete decoupling dominates and subsequent details are independent of the details of dust formation, depending only on final properties of the dust grains. Remarkably, they are able to predict from their general solution, that all optically thin winds share universal velocity and aerosol density profiles, including an interstellar, MRN power law distribution of emerging particles.

Particle growth: Based on the foregoing, we are left with a picture of the outer atmospheres of stars as turbulent regimes where nucleation occurs, producing tiny grains of corundum and small silicates which accelerate quickly due to radiative forces and decouple from the surrounding gas. Can we assemble a consistent picture that connects the gas-particle drift phenomenon with the observed quantities of amorphous and crystalline silicates? We turn to calculations by Chokshi et al. (1993) for insight regarding particle coagulation. Others have computed particle destruction in interstellar shocks, but Chokshi et al. deal with the issues of particle adhesion as a result of collisions. They find that not only do tiny particles accelerate better, but also show higher coagulation rates, neglecting charges.

4.0 OBSERVATIONAL PROSPECTS

We have assembled a picture of aerosols in circumstellar envelopes that includes the formation of nanoparticles which are accelerated to hypersonic speeds relative to the gas. Subsequent momentum coupling and grain growth then account for the mass loss observed in stellar winds. However, exactly how do the nanoparticles form and accelerate, and how do the subsequent particle shapes and dynamics relate to the observed diversity of stellar winds and planetary nebula shapes? Two of the most potent tools available at the beginning of the 21st century involve spectropolarimetry in the mid-IR, and very long baseline interferometry [VLBI] of maser emission, which we now discuss.

4.1 Spectropolarimetry

In the late 1940's, W.A. Hiltner and John Hall built the first astronomical optical polarimeters with the intent of measuring polarization signals emitted periodically from binary stars. Such an effect does exist, although they failed to detect it. They did however, observe that light from hundreds of stars, binary or not, is polarized, and that this polarization increases in magnitude with reddening, and that the position angles of polarization tend to be parallel to the Milky Way (Hiltner 1949; Hall 1949). On a historical note, notice that they published separately in 1949 due to the fact that the collaboration was aborted once they realized the magnitude of their discovery. It was during this time that Enrico Fermi announced his theory on the magnetic acceleration of cosmic rays; leading to the postulation that magnetic alignment of dust grains in the interstellar medium (ISM) is the cause of the anisotropic extinction of the starlight. In 1951, Hiltner then published polarization maps of the Galactic plane, from which Chandrasekhar & Fermi (1953) calculated a magnetic field strength on the order of a few micro-Gauss, the characteristics of which have been confirmed from observations of synchrotron emission, Zeeman splitting, and Faraday rotation. This was the beginning of the study of polarimetry in astronomy to not only to probe the dust characteristics in the galaxy, but in those from Young Stellar Objects (YSOs) to Planetary Nebulae (PNe).

There are two polarization mechanisms that arise from extinction of radiation: scattering and dichroic absorption and emission from aligned grains. Dichroism, as defined by Tinbergen (1996), is the differential extinction of orthogonally polarized radiation components. Dichroism is generally considered to be the dominant mechanism in the mid-infrared (2-15 microns wavelength), indicative of a characteristic shift between peak absorption and the peak polarization (Kobayashi et al. 1980). Dust particles both in the ISM as well as circumstellar envelopes (CSEs), are non-spherical, and/or have amorphous/crystalline structure. This results in a different extinction cross section for the two transverse components of the incident electromagnetic radiation. If the wavelength of radiation is short compared to an effective radius of the grain, scattering will be the dominant polarization mechanism. In the dipole approximation used for calculating the extinction cross-sections, (grain radius on the order of tenths the wavelength), the influence of scattering is diminished ($\alpha\ \lambda^{-4}$), and polarization due to absorption becomes dominant as it is $\alpha\ \lambda^{-1}$ (van de Hulst 1957; Bohren & Huffman 1983). From Kirchhoff's law, polarization due to absorption will be accompanied by polarized emission (Hildebrand 1988), and if scattering is negligible, the polarization components due to absorption and emission can be separated, as outlined by Aitken (1996). At wavelengths much longer than grain radius, where the dipole approximation is no longer valid, polarization due to emission is the dominant process and can be thought of in terms of Babinet's principle.

Infrared spectroscopy has long been used in laboratories to identify vibrational transitions that give rise to the resonance features characteristic of chemical bonds in the solid state. Astronomical studies of dust related spectral features should then provide a means of identifying the chemical properties of dust throughout the universe and to dissect the thermodynamics and magneto-hydro dynamics (MHD) associated with their formation in stellar winds. Although in practice, one finds that the application is not so straightforward. The source of radiation often suffers from large visual extinction making it difficult to define an extinction curve, and in the mid-IR, the observed spectrum often has components due to absorption and emission. The physical structure and chemical mix of the grains also contribute to the shape and position of the spectral feature, and spectroscopy only serves to identify the chemical bonds, leaving more detailed information as to the physical and chemical nature of the grains undeterminable.

If one can assume that the underlying source of radiation is unpolarized (an assumption that can be tested from the measurements), than the polarization spectrum is independent of the source spectrum, presenting a less complicated view of the dust grains. Independent information regarding the chemistry and structure of the grains is then available from spectropolarimetry since the polarization and extinction spectra are independent of one another (Aitken 1996).
As mentioned in the introduction, there are two competing polarization mechanisms brought on by the extinction of starlight from dust grains: 1) scattering and 2) dichroic absorption/emission from aligned grains. For pure scattering to occur, the effective grain radius must be much greater than the wavelength of radiation. Jura, et al. (2000), have suggested 20 μm to 0.2 cm grain sizes in CSE around select red giant stars, but the observations constrain the dimensions of measureable particles, per the dipole approximation:

$$\frac{2\pi\ a_{eq}}{\lambda} < 1 \qquad (3.6)$$

Where a_{eq} is the "equivalent" radius of the grain, which is the radius of the equivalent sphere having the same volume as the spheroid (Lee & Draine 1985). From the polarization measurements, it will become apparent whether or not this assumption is correct, but it's a good starting point as it provides a reasonable test for determining grain sizes in these environments (Hildebrand 1988). For wavelengths much greater than a_{eq} polarization due to dichroic emission dominates, but this occurs out in the far-IR and sub-mm region of the electromagnetic spectrum.

In the Dipole approximation, the scattering and absorption efficiency "*Q*-factors" are found from Mie theory to be:

$$Q_{sca} = \frac{8}{3}\left(\frac{2\pi a}{\lambda}\right)^4 \Re\left[\left(\frac{n^2-1}{n^2+2}\right)^2\right] = \frac{8}{3}\left(\frac{2\pi a}{\lambda}\right)^4 \Re\left[\frac{\varepsilon-1}{\varepsilon+2}\right]$$

and

$$Q_{abs} = \left(\frac{8\pi a}{\lambda}\right) \Im\left[\left(\frac{n^2-1}{n^2+2}\right)^2\right] = \left(\frac{8\pi a}{\lambda}\right) \Im\left[\frac{\varepsilon-1}{\varepsilon+2}\right]$$

Where n and ε are the complex index of refraction and complex dielectric function respectively (Bohren & Huffman 1983). This result is important to show the λ^{-4} dependence of the scattering efficiency in the dipole approximation. In the analysis that follows, scattering is assumed to be negligible in comparison to the absorption. Then, there is solely polarization due to absorption and emission, and a method for separating these two components can be exploited. If scattering is important, than the way in which the grain geometries and polarization mechanisms are calculated will be inconsistent with what is observed.

In the dipole approximation, it is possible to place constraints on the grain shape to first order, even though the polarization spectrum is mostly dependent upon the grain and mantle chemistry. In order to characterize the shapes of the grains, since they are most likely irregular and possibly aggregates of smaller particles, it makes the most sense to use a single parameter. This parameter, first derived by van de Hulst (1957) considered the effect of incident radiation on particles in the dipole approximation, deviating from spheres. This leads to the consideration of spheroids, a class of ellipsoids with either oblate or prolate grain shapes. Oblate can be thought of rotating an ellipse about its semi-minor axis, while prolate arises from rotation about the semi-major axis. Hildebrand & Dragovan (1995) compared measured versus predicted values of the polarizations using dielectric constants for astronomical silicate calculated by Draine (1985) for two interstellar clouds, the BN object in Orion and AFGL 2591. From their studies they found oblate grains with ratio of short to long axis ~2:3 to best fit the observed polarizations.

The spectral region from 2-15 μm plays host to a variety of ice and carbonaceous/silicate dust species, appearing in both emission and absorption. It attempting models to fit the absorption and emission profiles, it would be desirable to put constraints based on the arrangements of the dust species with respect to one another. Some of the more popular dust models have: 1) the ice and carbonaceous/silicate species physically separated; 2) the core- mantle arrangement; 3) fluffy aggregates. Spectropolarimetry can place a constraint on the dust grain morphology, primarily in providing a stringent examination of the core-mantle arrangement. Correlations in the polarization magnitude and position angle should exist amongst those species that occupy the same region of space. If there is no correlation, then it can be said that the species cannot exist in a core-mantle arrangement (Adamson et al. 1999; Aitken 1996; Holloway et al. 2002). So far, most of the spectropolarimetric work done has been toward understanding dust composition on galactic center objects and young stellar objects (YSOs). Two most recent examples of this are the observations of Holloway et al. (2002) on YSOs and models proposed by Li & Mayo Greenberg (2002) for the galactic center objects IRS3 and IRS7.

The spectropolarimetric observations of Holloway et al. (2002) were concerned with comparing polarization excess in the 3 μm ice features of YSOs with the 9.7 μm polarization of the silicate features observed by Smith et al. (2000). They found that good correlations exist between the polarization profiles of the two features, which would be indicative of ice mantles existing on silicate cores (Aitken 1996). More specifically, similar polarization position angles and specific polarization (polarization per optical depth) should exist. It is inconclusive to say that if correlations exist, than ice mantled grains exist, but if there is no correlation, then the core-mantle model can effectively be ruled out. Another important result, is that the dominant polarization mechanism in the near-IR was found to be due to dichroism. This was found by measuring a characteristic shift in wavelength from the peak absorption polarization values (Kobayashi et al. 1980). Li & Mayo Greenberg (2002) used spectropolarimetric observations to constrain a dust model based on near-IR observations of the 3.4 μm carbonaceous feature in IRS7 (M2 I super giant) and the 9.7 μm silicate feature in IRS3. Their model predicts that a similar degree of polarization should be measured for both spectral features in IRS7, where in this case, a silicate core/hydrogenous amorphous carbon mantle is being tested. Although no polarization was measured in the 3.4 μm feature in IRS7, the core-mantle model cannot be rejected due to the lack of 9.7 μm observations.

Just as valuable would be spectropolarimetric studies of late type stars, in whose environments matter is continually ejected into dusty envelopes on the order of a several stellar radii away from the stars themselves. The main difference between the study of late type stars and molecular clouds has to do with the formation and evolution mechanism of the grains (Hagen, Tielens & Greenberg 1983). In late type stars it is expected that the grains condense in the outflows of matter from the star, whereas in the ISM (which includes YSOs and galactic center objects), the grains are thought to condense in interstellar space, possibly undergoing continual UV photo processing. The cyclic evolutionary dust model (Mayo Greenberg 1989) predicts that interstellar grains will undergo approximately 50 cycles of processing in the ISM before they are consumed by star formation or become part of a comet (Mayo Greenberg & Li 1999). Thus, in studying dust in late type stars, one gets a glimpse of the raw products before they are ejected from the star and back into the ISM. Since correlations in polarization have been found between ice and silicate features, in support of a silicate core/ice mantle model, the processing of grains might begin with ices, being the precursor of the organic residue found in the ISM.

4.2 Interferometry

Recent decades have seen a flowering of success with radio and infrared interferometry, largely thanks to increased computing power. While the scope of this review does not permit an exhaustive summary, we will highlight current representative results that indicate the power of the method and implications for the studies of CSE aerosols.

The Infrared Spatial Interferometer (ISI) has a long series of successful mid-infrared measures, with high precision angular diameters for alpha Ori (54.7 milliarcsec) and omicron Ceti (47.8 mas at phase 0.90) among the latest reports (see Weiner et al. 2000 and citations therein).

The Palomar Testbed Interferometer (van Belle, et al. 2002 and references therein) has succeeded in resolving numerous AGB stars at K band wavelengths (2.2 microns). With milliarsecond resolution, in addition to providing evidence about fundamental mode pulsation, the work is beginning to separate optical depth effects in CO and water ice components of the K band, and finding evidence for elliptical shapes in more than a minority of AGB stars examined. This offers one of the best ways to test proposed equatorially enhanced mass loss (cf. Stencel 2000 and references therein).

Similarly, in the microwave regime, increasing numbers of stars have been resolved in terms of their SiO, H_2O and OH maser spot distributions, including the recent detection of collimated jet-like outflows in an AGB-like star (Imai, et al. 2002). These observed distributions and maps are challenging conventional interpretation, and open the way for novel observational efforts. Combined with new mid-infrared spectra potentially forthcoming from NASA's Space Infrared Telescope Facility (SIRTF) in 2003, further tests of the silicate shape-microwave maser chronology are possible (Stencel et al. 1990).

One additional observational method that deserves more attention is the production of X-ray halos due to scattering by dust (cf. Smith and Dwek 1998). Red giant stars paired with x-ray sources in binary stars should be examined for this effect.

5. 0 SUMMARY

We have reviewed recent research on the origin and composition of solids in the circumstellar envelopes of evolved stars, including dynamics and interaction between gas and solid phases in outflows. New observational prospects for clarifying numerous issues regarding aerosols were outlined. We thank Research Signposts for the invitation to create this review, Dr. Shanhu Li for useful references to the aerosol literature, and acknowledge support of the estate of William Herschel Womble to the University of Denver for making this work possible.

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(END)

Addendum, 3/4/2004:

Other than the pioneering, classic near-IR polarimetry of AGB stars by Johnson and Jones (1990), one of the key diagnostics of the dynamics of circumstellar envelopes is the maser emission from SiO molecules (v=1, J=1-0 and J=2-1) detected at 43 and 86 GHz. Recently, improvements in polarization calibration at high frequencies and total intensity multi-dish interferometric observations have demonstrated the SiO masers spots are confined to a narrow ring like morphology (tangentially amplified, cf. Diamond et al. 1994) around many late type stars, indicating orderly motions and systematic velocity distributions in the 1 to few stellar radius domain. As the SiO molecule is nonparamagnetic, if exhibits significant linear polarization in the presence of a magnetic field, enabling determination of magnetic field strength in this key region. Kemball and Diamond (1997) deduced a line of sight field strength in the Mira TX Cam of 5-10 gauss. Vlemmings et al. (2002) have compiled this and related magnetic field strength determinations for related stars using SiO as well as H2O and OH masers at correspondingly greater distances to indicate an inverse square law like variation of magnetic field strength with distance around evolved stars, and that the magnetic pressure dominates the thermal pressure by a factor of more than an order of magnitude. This clearly indicates how the dynamics can be affected by the magnetic field, much as proposed by Matt et al. (2000) who present a "simple, robust mechanism by which an isolated star can produce an equatorial disk. The mechanism requires that the star have a simple dipole magnetic field on the surface and an isotropic wind acceleration mechanism. The wind couples to the field, stretching it until the field lines become mostly radial and oppositely directed above and below the magnetic equator, as occurs in the solar wind. The interaction between the wind plasma and magnetic field near the star produces a steady outflow in which magnetic forces direct plasma toward the equator, constructing a disk. In the context of a slow (10 km/s) outflow (10^{-5} M_o/yr) from an asymptotic giant branch star, MHD simulations demonstrate that a dense equatorial disk will be produced for dipole field strengths of only a few Gauss on the surface of the star. A disk formed by this model can be dynamically important for the shaping of planetary nebulae." Similarly, we ask and plan to investigate with IR spectro-polarimetry whether these types of conditions can shape the dust particle geometry on micro and macro levels in AGB star outflows.

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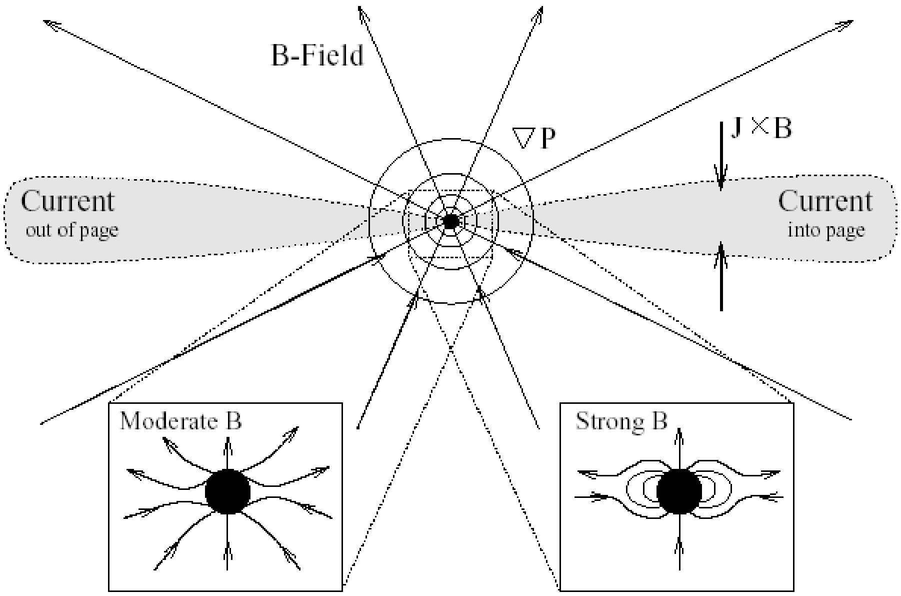

FIG. 1.—Qualitative cartoon of the model, including magnetic field lines and pressure contours, is shown. In steady state, a weak, initially dipolar magnetic field (**B**) becomes radial but oppositely directed above and below the magnetic equator, and a wind is driven isotropically from the surface of the star. An equatorial current sheet (**J**) exists to maintain the radial magnetic field. The resulting (**J** × **B**) force is directed toward the equator. For moderate (*left inset*) or strong (*right inset*) dipole magnetic fields, the magnetic force is sufficient to divert the wind toward the equator.

Figure 1 from Matt et al. 2000.