Effects on the Optical Spectrum

The main contribution to the observed reddening of the visible spectrum, which implies a total visual absorption $A_V \sim 3$ magnitudes in some cases, probably comes from dust occupying a more extended volume than that in which the observed infrared radiation and the line emission originate. The inclusion of grains therefore need not alter significantly the conclusions reached in earlier studies[12,13] of the excitation of the emission regions by a nonthermal ultraviolet source. One might, however, expect the dust selectively to attenuate resonance line radiation, which is subjected to repeated scatterings by the gas.

The nature of our proposed model is such that it does not allow any strong predictions concerning the energy output and spectrum of the central source, much of which may lie in the far ultraviolet. Some such information may be inferred from studies of the optical line emission. The central source will be reddened by the grains which surround it, and radiation scattered from these grains may contribute to the observed continuum. This effect would tend to increase the apparent angular size of the central source and the line emitting region.

Comparison with our Galaxy

It is extremely interesting that the total amount and spatial density of dust required to produce the observed infrared emission of Seyfert galaxies are not unreasonably large. Within the uncertainties of the model, in fact, the required 6 magnitudes kpc^{-1} of extinction is comparable with the 2·5 magnitudes kpc^{-1} observed towards the centre of our galaxy[16]. This supports the view[17,18] that a Seyfert galaxy may be a normal spiral in which an explosive event has produced a strong central source of radiation. Strong far infrared radiation from the direction of the galactic centre has recently been detected by Hoffmann and Frederick[19]. It is likely that this radiation can be explained by a grain model of the type we suggest. It would then follow that the galactic radiation is concentrated at 100 μm, and not at 10 μm (as for Seyferts), because there is no compact ultraluminous body at the centre of our galaxy. In fact, Hoffmann and Frederick were unable to resolve the galactic centre emission in galactic longitude, and deduced a minimum extent for the 100 μm radiation of 6°·5 in the galactic plane. This corresponds to a distance of ~ 500 pc from the galactic centre, and the diffuse nature of this radiation is itself indicative of a dust model.

Conclusions

We have examined some of the consequences of attributing the infrared radiation from Seyfert galaxies to thermal emission from grains. The present observations are well satisfied by a relatively simple model in which a bright central object is embedded in a large cloud of grains at a density comparable with the density of grains in the central regions of our galaxy.

We hope that our conclusions and predictions may soon be tested. A crucial observation would be to measure the infrared output and spectrum of Seyfert galaxies with variable apertures which are sufficiently small to exclude radiation from the stellar component. Such measurements may be possible only for the nearer objects, and only at the longer infrared wavelengths. Measurements of the total flux as a function of aperture may yield useful information about the nature of the grains and/or the luminosity of the central object. Spectra taken with the smaller apertures must be flatter if our picture is correct. If this prediction is not verified, or if the infrared radiation shows rapid variations in the far infrared ($\lambda \gtrsim 10$ μm), it may be necessary to invoke other mechanisms to explain the infrared fluxes. The discovery of polarization would not necessarily indicate a non-thermal model, for the emission from magnetically aligned grains could be highly polarized[20].

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Windblown Dust on Mars

by

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The wave of darkening in the Martian springtime, which some say may have a biological explanation, can be explained in terms of windblown dust.

In the Martian springtime there is a sequential enhancement of contrast between bright and dark areas, called the wave of darkening, which statistically occurs first at higher latitudes although there are marked variations in behaviour for individual areas[1–3]. The biological explanation of the darkening is that organisms inhabiting the dark areas grow and reproduce during the Martian spring[4]. An alternative hypothesis is that the seasonal darkening of the dark areas is due to the movement of dust particles to the bright areas[2,5,6]. Here we shall develop the windblown dust model, starting from the assumptions of major elevation differences on Mars, the presence of fine dust, and of winds adequate to move the dust. All three assumptions have some measure of observational support.

We begin by estimating the dependence on particle size and atmospheric density, ρ, of the minimum or

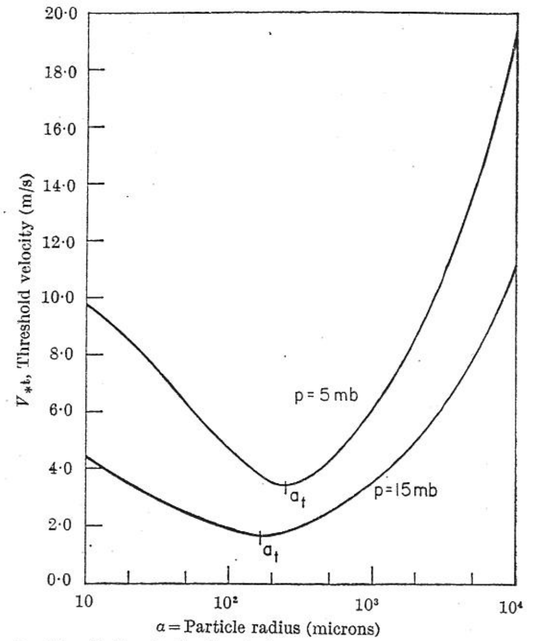

Fig. 1. Threshold velocity for dust mobility on Mars as a function of particle radius, for two choices of total surface pressure.

"threshold" stress, S_t, that must be exerted by surface winds to set grains in motion. Instead of S_t, it is usual to introduce V_{*t} defined by $S_t = \rho V^2_{*t}$. Following the classic procedure outlined by Bagnold[7], Ryan[8] calculated V_{*t} for Martian conditions, but for higher surface pressures than are currently indicated. Fig. 1 shows a recalculation of V_{*t} as a function of particle radius for pressures believed to be representative of highland and lowland areas on Mars[9]. An important feature of the curves is the minimum threshold velocity near 200 microns radius. Usually all particles with V_{*t} below the local meteorological value of V_* will be set into motion. For any grain motion to occur, V_* must, evidently, exceed $(V_{*t})_{min}$, the lowest value of V_{*t} for any particle size.

We see from Fig. 1 that, for all particle sizes, V_{*t} is larger in the highlands than in the lowlands. The density dependence of $(V_{*t})_{min}$ is particularly interesting. A comparison of the two curves of Fig. 1 with each other and with Ryan's calculations at high pressures shows that $(V_{*t})_{min} \propto \rho^{-2/3}$. This can also be derived analytically[9]. It is highly unlikely that the dependence of V_* on ρ will exactly offset the dependence of $(V_{*t})_{min}$ on ρ, so the existence of sizable elevation differences on Mars implies that dust is more easily raised at some locales than at others. If some of the dust can be carried sizable distances, so that there is effective exchange of material between highlands and lowlands, particle size segregation and a consequent contrast difference will be established; the smaller particles will tend to be brighter (see, for example, ref. 22). We can thus understand the existence of bright and dark areas on Mars without invoking differences in chemical composition.

Rather large values of the wind velocity are required to produce dust storms on Mars. If we assume that conditions of neutral stability hold throughout the frictional boundary layer, then[9] we find that wind velocities in excess of 300 km h^{-1} above the boundary layer are required to initiate grain movement for a surface pressure of 10 mbar. But the lower atmosphere of Mars is highly unstable during the day[10,11], so milder winds than indicated are required to start dust movement[10]. Expected uncertainties[9] in $(V_{*t})_{min}$ are factors of two or three. Also theoretical calculations indicate average wind speeds of about 100 km h^{-1}, again with an uncertainty of a factor of two or three, and gust velocities may be considerably larger[11-13]. It is interesting that transverse velocities $\sim$100 km h^{-1} or higher of large dust clouds on Mars have been reported by de Vaucouleurs (ref. 14, and a symposium on the surface of Mars, New York, 1967). Thus large scale winds may indeed be capable of producing Martian dust storms, but V_* will not then greatly exceed $(V_{*t})_{min}$. We assume that, characteristically, $V_* \simeq 1{\cdot}5\ (V_{*t})_{min}$ during a dust storm.

Owen (quoted in ref. 15) and Neubauer[10] have drawn attention to the part that dust devils may play in raising dust on Mars. Typically, these small scale disturbances are generated when the surface temperature greatly exceeds the mean air temperature, as occurs on Mars[11,16]. Contrary to Neubauer's claim, large scale winds do not induce high vortex velocities within a dust devil. Indeed, intense large scale winds inhibit the formation of dust devils[17,18]. The high velocities attained inside dust devils (on the Earth, speeds of 100 km h^{-1} have been measured) are due to angular momentum conservation as air spirals from exterior to interior. It is not clear that dust devils will be important on Mars—the large scale wind velocities may always be too great for them to form. And if the air is too unstable, as it may be on Mars, spontaneous convection currents may arise in many locales, preventing the formation of dust devils. If dust devils are frequent on Mars, V_* may greatly exceed $(V_{*t})_{min}$ and very large vertical velocities may occur within them.

There are three types of transport[7] once motion has begun: suspension, saltation and creep. Once small particles are lifted off the ground, eddy currents are able to carry them to considerable heights; in the absence of further turbulent support such particles fall out according to the Stokes–Cunningham equation and, until they reach the surface, are described as suspended. Particles of intermediate size are lifted by winds to only modest heights, along modified ballistic trajectories, and quickly return to the ground; this motion is called saltation. Finally, larger particles may be moved, not by the wind itself, but by momentum exchange with saltating grains; these particles never leave the ground but "creep" slowly in the direction of the wind. Saltating particles may also exchange momentum with smaller grains, lifting them into suspension. Only those dust grains put into suspension can be exchanged between major topographical areas, in timescales of the order of a year or less.

Suspension occurs for particles with radii less than some critical value, a_s, as gravity is a volume force and aerodynamic lift a surface force. When the vertical winds are predominantly upward, as within a dust devil, we expect that a_s can be obtained from an exact equality between the vertical wind velocity and the terminal velocity. For dust devils, the vertical wind velocities are comparable to the horizontal wind velocities. When we use a logarithmic velocity profile to relate V_* to the velocities near the top of a particle's trajectory[8], we find for all values of V_* that a_s significantly exceeds the largest particles that can be set into motion. Thus a dust devil initially puts all particles that it moves into suspension. This result should be insensitive to the choice of velocity profile.

To estimate a_s for Mars in the case of motion caused by large scale winds, we take the ratio of the terminal velocity to the critical vertical velocity near apapsis to be constant and assume that the latter scales as V_*. Thus $a_s \propto (V_*/g)^{1/2}$, where Bagnold's laboratory[19] results are used to define the proportionality constant. When $V_* = 1{\cdot}5\ (V_{*t})_{min}$, this implies $a_s \simeq 125$ microns at the 10 mbar pressure level on Mars, and only slightly different results at other pressure levels.

This value for a_s provides a lower bound on the grain sizes participating in saltation. An upper bound is given by the condition $V_{*t} = V_*$. For large scale winds, subject to the constraint $V_* = 1{\cdot}5\ (V_{*t})_{min}$, an upper bound of about 550 microns at the 10 mbar level is obtained on the size of saltating particles. No saltating particles are expected in dust devils. If V_* greatly exceeds $(V_{*t})_{min}$ for dust devils, then particles ranging in size from microns to centimetres could be put into suspension. Creep occurs only when saltating particles are present, and for particles with a maximum size about six times that of the saltating grain[7].

How far will grains put into suspension on Mars travel before returning to the ground? As a first approximation we assume that particles initially lifted to half a scale height, or 5 km, remain airborne for a time determined by their terminal velocities. Their lateral motion then equals their fallout time multiplied by the mean windspeed, here taken to be 50 km h^{-1}. We find 5, 75, and 500 micron particles travel 6,500 km, 50 km and 1 km respectively. Thermal convection leads to sizable vertical wind velocities throughout the daytime troposphere, velocities comparable with the terminal velocity of a 300 micron particle[20]. No such winds are predicted for night-time. Particles with 100 micron radii will therefore travel greater distances than calculated, while much smaller particles remain unaffected, because their lifetimes are longer than 12 h; particles much larger are unaffected by thermal convection. We infer that all particles put into suspension by large scale winds will travel distances comparable with those between bright and dark areas, while only those particles with radii less than 200 or 300 microns, put into suspension by dust devils, will travel far from the dust devil. In both cases, locales characterized by frequent dust storms will be denuded of their smaller particles, and so will appear dark.

We now attempt to correlate dust storm frequency with elevation. We have already found that $(V_{*t})_{min} \propto \rho^{-2/3}$. We now inquire into the ρ-dependence of V_*, assuming, for convenience, $V_* \propto \rho^{-n}$. To first order, for dust devils, $n=0$; dark and bright areas on Mars have very similar peak surface temperatures[20a] and hence similar temperature discontinuities between surface and air. In this case, dust is less easily raised in highlands, and dark areas should be lowlands. For large scale winds, the equation of mass continuity implies $n=1$, and therefore that dark areas are highlands. While the analysis seems to imply that dark areas are highlands if dust is raised by large scale winds and lowlands if by dust devils, more detailed analyses are certainly warranted. For example, because windward sides of elevations are less sheltered than leeward sides, there may be a tendency for windward sides to be darker[9].

In any season we expect an equilibrium between the mass flux of small particles exchanged between bright and dark areas such that the relative concentration of small particles (and hence contrast differences) varies inversely with the relative frequency of dust storms in the two locales. Because of seasonal variations in the wind patterns and in temperature discontinuities between surface and atmosphere, the absolute and relative frequencies of dust storms should also vary seasonally, leading to a darkening cycle with the seasons. The time of greatest relative dust storm frequency (although not necessarily of greatest absolute frequency) will be the time of maximum darkening. To deal with relative frequencies we need a crude knowledge of the V_* distribution function. Because we lack this for dust devils, we can make no predictions on the time of maximum darkening for grains raised by dust devils. For large scale winds, theoretical calculations show velocities to be about a factor of three larger in winter than in summer[9,13]. We assume a Gaussian distribution of wind velocities, and expect $(V_{*t})_{min}$ during summer to correspond to a position on the high velocity tail of the velocity distribution function. On this basis, sample calculations[9] indicate that the relative frequency of dust storms and hence the seasonal darkening should reach a maximum during the beginning of the summer, in agreement with observations.

We now compare our windblown dust model with observations.

(1) According to the model, the bright areas are composed chiefly of small, exchangeable dust grains, and so yellow clouds should have a marked photometric resemblance to the bright areas. This is the case[21]. (2) Photometric, polarimetric and thermal inertia data all indicate that the dark areas are composed of a powdered material just as are the bright areas[20a,22]. (3) It is evident that the deposition of fine dust cloud material will brighten an area. Our model shows that the removal of small particles by a dust storm can darken an area, especially if it is already a dark area, or desert region close to a dark area. There is almost direct photographic and photometric evidence for this[21,23]. (4) We have seen that particles of radii less than about 100 microns will be exchanged between bright and dark areas when large scale winds are the mechanism for dust raising; and less than about 250 microns for dust devils. Bright areas will consist primarily of such particles and so should be characterized by a mean particle size calculated to be some tens of microns. Both photometric and thermal inertia analyses again indicate particle sizes in agreement with this prediction[22]. Similarly, we expect that outside seasonal darkening, the mean particle size of dark areas will be determined by a mixture of exchangeable and suspendable, non-exchangeable suspendable, and saltating particles (particle sizes of about 100 to 400 microns). Photometric analysis again indicates such sizes outside of and during darkening, with the exact numerical results in better agreement with the predictions for large scale winds than for dust devils[22]. Particle sizes inferred from thermal inertias for several dark areas are in agreement with the photometric results[20a]. (5) There will be an upper bound to the contrast that dark areas can achieve; it occurs when all the exchangeable particles are removed. Such a phenomenon is indicated in a histogram presented by Focas[23] of the maximum degree of darkening for the centres of various dark areas. This diagram indicates a lower bound of 0·43 on the ratio of the brightness of the dark areas at 5800 Å to that of reference bright areas. Because the two intervals closest to 0·43 have the largest populations, we infer that this bound is real and not the result of unfavourable statistics. This limit corresponds[9] to an average particle size of about 300–350 microns, in agreement with our predictions. (6) The model emphasizes particle size modulation rather than chemical change as the cause of seasonal darkening. Analysis of the polarimetric changes that occur during darkening supports this view[22]. (7) If a bright area initially contains a significant number of non-exchangeable particles, then it can be expected to brighten at the same time that adjacent dark areas darken; it will receive the smaller particles lifted off the dark areas. This prediction is unique to the windblown dust model of seasonal changes, and would be difficult to understand in a biological model. We expect that the southern hemisphere bright areas, where there are many adjacent dark areas, would be more likely to show this effect. Fig. 2 shows confirmatory photographic evidence. The Hellas–Eridania area, at top left, has a lower albedo than the bright area to its right and bottom. The photograph at right displays the seasonal darkening. Here, Hellas has an albedo comparable with the reference bright areas. Photographs from the Lowell Observatory Documentation Center confirm these results, and there are similar photographs for the 1954, 1956 and 1958 oppositions[24]. Elsewhere[9] we have argued that the particular instances of brightening cited are not the result of the presence of either clouds or frost deposit.

The windblown dust model can also explain the rapid regeneration of dark areas temporarily covered by bright material; winds would quickly return the fine powder back into suspension[25]. Secular changes in the configuration of bright and dark areas can be understood in terms of shifting wind patterns; the areas most susceptible to these irregular modulations seem to have the smallest extents and apparently the shallowest slopes[25]. Certain

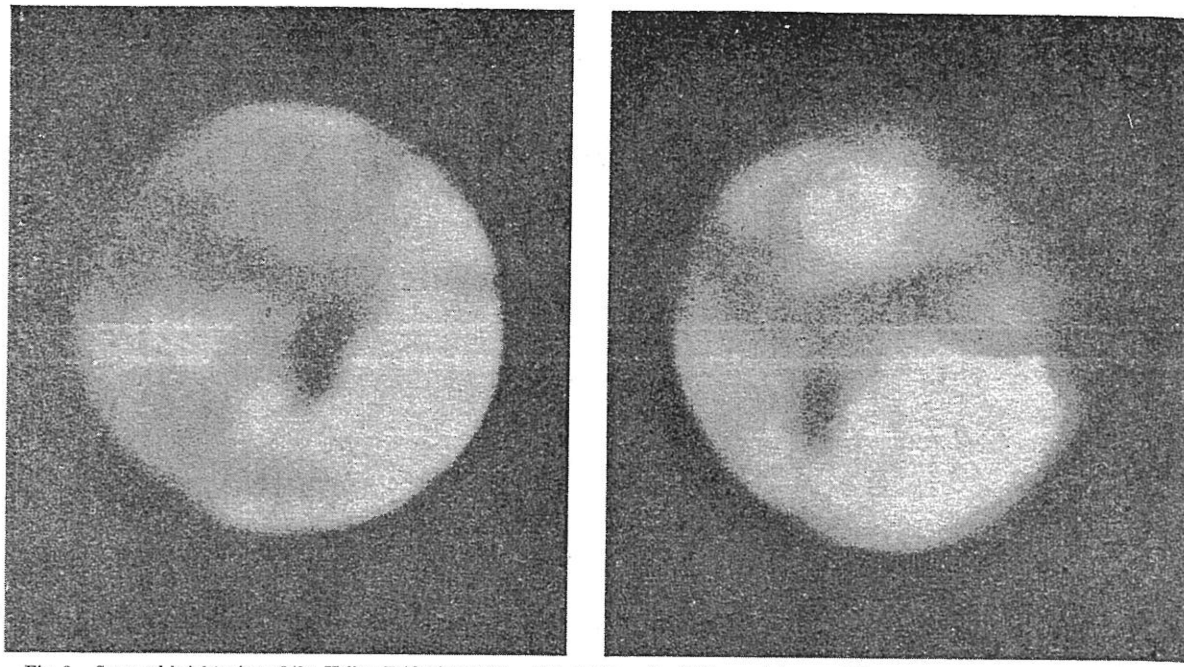

Fig. 2. Seasonal brightening of the Hellas–Eridania region. The photograph at left was taken on July 3, 1907 (Martian date, April 7); the photograph on the right was taken on October 4, 1909 (Martian date, July 1). After Slipher, 1961.

properties of the Martian canals can also be understood within the context of this theory[26]. The success of wind-blown dust models does not, of course, argue against life on Mars.

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New Theory of Mid-latitude Sporadic E

by

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Unified explanations have been derived for the main statistical and structural characteristics of sporadic E.

ROCKET-BASED measurements of electron density have shown that sporadic E reflexions are caused mainly by overdense layers of ionization extending for horizontal distances of several hundred kilometres[1]. Layers that lie above about 115 km are usually several kilometres thick and have rounded profiles. Below 115 km narrow steep-sided layers, often with complex internal structure, are regularly observed.

Measurements of ion composition by rocket-mounted mass spectrometers have shown that narrow overdense layers below 115 km consist mainly of long lived metal ions[2,3]. These observations point to vertical redistribution of neutral ionization as causing layer formation. Neglecting production and loss processes and the effects of diffusion, all of which are likely to be unimportant during the formation of a narrow layer composed mainly of metal ions, we may write for the electron density $N(z,t)$:

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial z}[w(z,t)N] = 0 \qquad (1)$$