In the calculations involving the atmosphere and hydrosphere the thickness of the crust is assumed to be ten (or twenty) miles.

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DARK NEBULAE

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1. It is now generally believed that many of the dark markings in the Milky Way, and dark starless regions in the sky, are produced by the interposition of huge obscuring clouds between us and the remoter stars. A long list of such dark markings has been given by Barnard, who has done more than any one else to point out their importance and probable nature. In some cases, as in the Pleiades, Orion and Ophiuchus, these "regions of obscuration" merge into faintly luminous nebulosity in the vicinity of certain stars, in such a way that there can be no doubt that they lie near these stars in space.

It thus appears that the obscuring masses or dark nebulae in Ophiuchus and Scorpius are at a distance of from 100 to 150 parsecs, those in Taurus at probably about the same distance, and those in Orion some 200 parsecs from us, while the dimensions of the individual clouds are themselves measured in parsecs.

The occurrence of these three great regions of obscuration within a distance which is so small compared with that of the galactic clouds indicates that such objects are probably of great cosmical temperature.

2. These dark nebulae usually appear to be quite opaque. In some cases the stars can be seen faintly through them, apparently without much change in color; but in certain instances stars imbedded in dense luminous nebulosity are abnormally red.

Of the various forms in which matter may be distributed in space, by far the most efficient in producing obscuration is fine dust, since this has the greatest superficial area per unit of mass. In a cloud composed of spherical particles of radius \( r \) and density \( p \), distributed at random so that the average quantity of matter per unit volume is \( d \), the extinction of a beam of light in passing through this cloud will be \( e \) stellar magnitudes per unit of distance, where \( e = 0.814 \, qd/pr \).
The numerical factor is independent of the physical units which are employed. The factor \( q \) is introduced to take account of the complications which occur when the size of the particle becomes comparable with the wave-lengths of light.\(^3\) For particles more than two or three wave-lengths in diameter \( q \) is sensibly equal to unity. For smaller particles it increases and is a maximum, 2.56, when the circumference of the particle is 1.12 times the wave-length. It then rapidly diminishes and becomes nearly equal to \( 14/3 \times (2\pi r/\lambda)^4 \) for particles of less than half this diameter. The ratio \( q/r \) is a maximum, 2.42, when the circumference equals the wave-length.

For clouds of the same mean density \( d \) the opacity reaches a sharp maximum when the particles are of this size. At the same time the absorption changes from the non-selective type to the selective type, varying as \( \lambda^{-4} \). For visual light the maximum opacity occurs when the radius is 0.086 \( \rho \). A cloud of particles of this size, and of the density of rock (2.7), will exert an absorption of one magnitude if it contains only 1/86 of a milligram of matter per square centimeter of cross-section, regardless of its thickness. If the particles are of half this size, or smaller, the selective absorption is almost as complete as for a gas, but may be nearly 100 million times as great.

Obscuration of light in space, therefore, whether general or selective with respect to wave-length, will be produced mainly by dust particles a few millionths of an inch in diameter, unless such particles form a negligible proportion by weight of the obscuring cloud.

3. It is just these particles, however, which will be most influenced by the pressure of the radiation of the stars. Calculations from more accurate data confirm Schwarzchild's conclusion that for a particle of the optimum size and the density of water, the repulsive force of the sun's radiation is about ten times the gravitational attraction, and show that for stars of the same brightness, but other spectral types, the radiation pressure will be about two-thirds as great for Class M and increase for the whiter stars, till for Class B it is fully ten times as great as for solar stars.

Dwarf stars will hardly repel dust at all, but giant stars, and especially the very luminous one of Class B, will repel it very powerfully. Only the coarser particles can come near such a star—the finer ones being driven away. This selective removal, from the vicinity of bright stars, of the particles which are most efficient in cloud formation, may explain the fact that the luminous portions of these dark nebulae, though centered upon stars, do not brighten up in their immediate neighborhood as much as might have been anticipated.

The finest dust must continue to be repelled by the stars, whatever their distance. It may congregate to some degree in interstellar regions,
where the repulsive forces from stars on opposite sides are nearly equal, but it can be in no true equilibrium there, and must ultimately escape to an indefinitely great distance.

4. Some force, however, operates to hold these dark clouds together, for their outlines are often sharp. This is probably the gravitational attraction of the cloud itself.

Taking a spherical cloud as an example we find that, if its mass is $M$ times that of the sun, and its radius $R$ parsecs, the velocity of escape at the surface is $0.092M^{1/2}R^{-3/2}$ km./sec. The internal velocity of the nebular material is known only in the case of the Orion nebula, where the luminous gas shows irregular variations in radial velocity from point to point, amounting to about 5 km./sec.$^4$ on each side of the mean.

For a nebula 1 parsec in diameter (which may be taken as a rough representation of the small black, almost round spot about 15' in diameter, discovered by Barnard$^4$ in Ophiuchus) the mass must be 60 times that of the sun, if the escape velocity is to be 1 km./sec.

If all this matter were in the form of particles of rock of the optimum size, the extinction for light passing centrally through the cloud would be 2000 magnitudes. An extinction of 10 magnitudes (quite sufficient for opacity) would be produced if the radius of the particles were 72 $\mu$.

Though these numerical values are largely conjectural, it appears probable that the aggregate mass contained in one of these great obscuring clouds must be very considerable—probably sufficient to form hundreds of stars—and that a sensible fraction of the whole mass must be in the form of dust less than 0.1 mm. in diameter.

It can easily be shown that any dust cloud which is impervious to light must also be impervious to particles such as those of which it is composed (and to free-moving electrons as well) in the sense that such a particle could not traverse the cloud without a practical certainty of collision. These collisions may account for the existence of dust within the clouds, even if it was not a primitive constituent.

5. The transition from these dark nebulæ to luminous nebulæ in the vicinity of the stars appears to occur in two ways. The first is by simple reflection of the light of the stars—which appears to occur in the nebulosity surrounding the Pleiades, the star $\rho$ Ophiuchi, and probably in many other cases. The second is by the excitation of gaseous emission, as in the Great Nebula of Orion, which is connected with one of the greatest known regions of obscuration and itself shows signs that obscuring masses lie in front of it.

Both theoretical considerations, as suggested by the writer$^5$ and the facts of observation collected by Hubble,$^7$ indicate that the luminosity of gaseous nebulæ is probably due to excitation of the individual atoms by radiations of some sort (etherereal or corpuscular) emanating from neigh-
boring stars of very high temperature. In the Orion nebula the stars of the Trapezium (θ Orionis) appear to be the source of excitation.

There is no reason to believe that the luminous gas forms the whole, or even any large part, of the matter present within the region—only that it is selectively sensitive to the incident excitation, and therefore gives out most of the light, just as the gases (carbon compounds and nitrogen) do in the coma and tail of a comet.

If the turbulent motions of the various parts of this nebula are of the same order of magnitude in the other two coordinates as in the radial direction, they must correspond to an average proper motion of 1.5 astronomical units per year, or about 0".8 per century (with Kapteyn's parallax of 0".0055). In a million years this would carry a nebulous wisp through 2°, which is more than the whole extent of the nebula.

It appears probable, therefore, that the aspect of the Orion nebula was entirely different a million years ago from what it is now, as regards its details. There is no reason, however, to suppose that the nebula was not there. We may rather imagine that wisps and clouds of dust, carrying gas with them, are slowly drifting about. Some of them pass through the field of excitation due to the radiations from the Trapezium stars, and, when in this field, the gas is set shining—faintly near its outskirts, and without excitation of the nebular lines; more strongly, and with the nebular lines, near the middle.

According to unpublished investigations by Hubble, it appears probable that the absorbing clouds in Orion, not far from the nebula, weaken the light of stars behind them by at least ten magnitudes. The exciting radiations probably penetrate to a relatively small depth into the mass and, even if they went deeper, little of the excited light could get out again. The Orion nebula, on this hypothesis, may be regarded almost as a superficial fluorescence of the gaseous portion of this vast dark cloud, in the limited region where it is stimulated by the influence of the exciting stars.

5 *Publications of the Lick Observatory, Berkeley, Cal.*, 13, 1918 (98).