The Galactic Nebulæ*

By J. H. Reynolds

THE relationship which exists between the dark galactic clouds, the luminous diffuse nebulosities and the involved or neighbouring stars is now generally recognised, but it has been only during the last twenty years or so that the real connexion between them has become evident, owing principally to the work of Slipher and Hubble. The luminous nebulosities, such as that surrounding θ Orionis and ρ Ophiuchi, are regions on the near side of obscuring clouds, illuminated by stars within effective range. The medium composing the clouds is lit up in two ways, depending on the temperature of the stars involved. Stars of *B*0 type and higher temperatures excite and ionise the atoms of the cloud by intense ultra-violet radiation, the resulting characteristic radiations being principally hydrogen, oxygen (singly and doubly ionised in the metastable state), and helium. With stars of lower temperature than *B*2, the illuminated cloud gives a continuous spectrum of the same type as the stars, which we may reasonably interpret as reflected light, while nebulosities surrounding intermediate stars show a combination of both types of spectrum.

Although the great advance in nebular astronomy during the present century has been entirely due to photography, since the pioneer work of Common and Roberts in Great Britain, and Keeler in America, the blotting out of the involved stars by over-exposure has had the effect of masking the apparent luminosity relationship between the stars and the surrounding nebulosity, so that some of the galactic nebulæ came to be regarded as independent formations. As an example of this I may mention Wolf's photograph of Nebula N.G.C. 7023 in Cepheus (Fig. 1). No one would think from the photograph that any star was involved in the nebula at all, although it is in fact the nebulosity surrounding the star B.D. 67°.1283. This brings me to a point which seems not to have met with the consideration it deserves, and that is the real relationship between the magnitude of the star and the surrounding nebulosity. It is evident that the apparent relationship depends for one thing on distance. If, for example, the Great Nebula in Orion were twice its actual distance the involved stars would be reduced to a quarter of their present brightness, while the apparent luminosity of the surrounding nebulosity would be still the same as at present, although reduced in size to half its angular diameter.

There is another complication introduced by the type of instrument employed. Broadly speaking, the apparent brightness of a star in the telescope depends on aperture, while the brightness of the surrounding nebulosity depends on focal ratio. By using a short focus reflector or lens we can increase the intensity and extent of a nebulosity; but the photographic result is apt to give a very erroneous impression of its real brightness, or rather faintness. A third modification is introduced by the three dimensional form of the nebulosity, which makes it impossible to say what is the real local distribution of intensity in an irregular cloudlike formation. It seems, therefore, impossible to measure the true ratio of intensity between any particular point of nebulosity and involved stars; but it is possible to measure with advantage the light distribution in planetary nebulæ, as these are usually symmetrically shaped formations, and consist of concentric gaseous shells transparent to their own radiations.

FIG. 1. Star involved in nebulosity, N.G.C. 7023.

The first to realise the true character of the dark obscuring clouds in the Galaxy was Barnard, who

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* From the Presidential Address delivered to the Royal Astronomical Society on February 14.

used a 6 in. short focus lens. Their extent must be enormous, as they cover many square degrees of the sky in Orion, Cygnus and other regions in and about the Galaxy. Their edges are usually luminous, although there are some well-known exceptions to this. Thus the North America Nebula in Cygnus is really the luminous edge of an extensive dark cloud (Fig. 2). On one side of the bright edge star-counts give only 10 per cent of the number on the other, where the normal stellar background of the Galaxy is shown with little or no obscuration. The same applies to the long filaments of nebulosity N.G.C. 6960, 6992 in Cygnus, although in these cases the disparity of star-counts on either side is nothing like so marked, owing either to a shallower depth of the absorbing medium, or a greater rarefaction, or both in some degree. There seem to be indeed all degrees of density of the absorbing medium between complete opacity at a shallow depth, such as the dark nebulosity near ζ Orionis, and a scarcely perceptible dimming of the stars by a light veil.

FIG. 2. North America Nebula in Cygnus, N.G.C. 7000.

We come now to the important question of the composition of these clouds. In the case of the Orion Nebula and others giving a gaseous spectrum, we have quite definite evidence as to their nature. They consist of hydrogen, singly and doubly ionised oxygen in the metastable state, and helium. These radiations extend for a range of about eight light years from θ Orionis if we take the usually accepted distance of 180 parsecs. As might be expected, the singly ionised oxygen represented by λλ 3727/9 extends much farther away from θ than λλ 5007, 4959, the radiations of doubly ionised oxygen. Hydrogen seems to be almost co-extensive with singly ionised oxygen, while helium is found mostly in the central regions. We have therefore to deal with elements of low atomic number, which form a large part of our own atmosphere. It seems curious that there is not more evidence of nitrogen in these clouds, another gas of low atomic number and very widespread in our atmosphere. The explanation seems to be that singly ionised nitrogen in the metastable state has two strong radiations at λλ 6584, 6548, but no other radiations occur within accessible range. Both these radiations are conspicuous in some of the planetary nebulæ, although I cannot find that they have been identified yet in the Orion Nebula.

It has often been assumed that the clouds must consist of solid particles owing to the fact that they reflect the light of neighbouring stars, and have a strong absorbing effect. But there is definite evidence that there can be no considerable amount of solid particles in the gaseous nebulæ, as such particles would tend to absorb the radiations from the gases, and give a continuous spectrum. It is now generally accepted that the characteristic radiations of the gaseous nebulosities are due to the ionisation of the gases in the cloud by the strong radiation of ultra-violet light or streams of electrons emitted by the high-temperature stars involved. When the effective distance limit of this ultra-violet radiation is passed, the atoms being no longer ionised would naturally be present in their neutral condition. There seems to be no valid reason why these neutral atoms should not form molecules, and even enter into combination with atoms of other elements to form molecules of water vapour and, if nitrogen is present, of ammonia. Owing to the low temperature of interstellar space, such molecules could scarcely exist in a gaseous or liquid form. Is it not, therefore, possible that the 'dust' which causes the reddening of the light of stars involved in or behind the clouds, and reflects the light of stars of temperature lower than *B*2, may be particles of frozen water vapour and perhaps ammonia ? In any event, all the evidence we have is that only gases of low atomic number are present ; but we do not know enough of the physical conditions to answer the question.

Fig. 3. A planetary nebula, N.G.C. 7635.

Perhaps the most extraordinary examples of the 'reflexion' nebulæ are the 'variable' nebulæ. Three of these are known—Hind's variable nebula in Taurus, near τ Tauri, N.G.C. 6729 in Corona Australis, and Hubble's variable nebula in Monoceros. All three are connected with variable stars and dark obscuring clouds, but it is the last two that are specially interesting.

Knox Shaw has made a detailed study of N.G.C. 6729, in the Helwân Bulletins. The dark cloud against which the variable nebula is projected is very dense, and the edge is not illuminated, although there are two conspicuous patches of luminous nebulosity surrounding two stars, which must be on the near side of the cloud. The form as well as the brightness of the nebulosity varied to some extent with the magnitude of the star, but there was only a rough correlation between the two. The projected outline of both N.G.C. 6729 and Hubble's Variable Nebula is comet-like, and is comprised irregularly within an angle of 60° with the variable as the apex.

The illumination of the nebulosity N.G.C. 6729 is consistent with the idea that the light of the variable star is transmitted to the cloud with the velocity of light, if a distance of about 120 light years is accepted. But the most striking evidence for this is afforded by Slipher's spectrographic investigation of these two variable nebulæ, for both the stars and the nebulosities gave a spectrum similar to the earlier spectrum of novæ. Bright hydrogen lines are specially conspicuous, with absorption on the edges of shorter wave-lengths, and bright helium also appears with many other radiations found in Nova Aurigæ at an early stage.

Although the planetaries give the same type of spectrum as the gaseous diffuse nebulosities, they are totally distinct in their origin and characteristics. There is no doubt now, I think, that they originated as new stars. The concentric, or almost concentric, shells of gas were blown out from a nova at the original outburst, and have been travelling outwards for many thousands of years in most cases, at velocities slow compared with those of the original outburst. Nova Aquilæ in 1918 was the first of these outbursts to give us the clue, and Campbell's classic work on the planetaries, of which details can be found in the *Lick Obs. Bull.*, vol. 13, gave us the corroborative evidence we wanted. It is true that Nova Persei in 1901 showed a rapidly expanding luminous shell, but this Kapteyn interpreted at the time as the passage of light outwards in a cloud. This explanation still holds good, as the parallax of this star is so small that no other seems to account for the extremely rapid growth of the shell. In six months it had expanded to an angular distance of between 6′ and 7′ from the star. This first luminous ring was followed by a much smaller nebulous envelope which had expanded to about 30″ in diameter by 1926. It is of irregular form, and from the curious hook-like form of its spectral lines is still expanding at a considerable rate.

The great majority of planetary nebulæ are almost symmetrical about an axis, and are either elliptical or circular in outline. In some cases the gases are concentrated in the outer rim of the shell and it is not so long ago that 'ring' nebulæ were differentiated from the planetaries in the catalogues, the N.G.C. for example having a different symbol for each.

We know now, of course, that the central stars which are of *O* type, and probably dwarfs, are the cause of the illumination of these enormous globes and shells of gas, by strong radiation in the extreme ultra-violet. The slitless spectrograph of the Crossley reflector at the Lick Observatory gave separate images along the spectrum, and the comparative diameters of these show much the same sequence as the diffuse gaseous nebulæ. The smallest images are helium and doubly ionised oxygen, and the largest are singly ionised oxygen (both in the metastable state), and hydrogen. In a good many cases singly ionised oxygen is not represented at all.

Like the new stars, the planetaries usually are found near or in the Galaxy, and their parallaxes are small. But if novæ are responsible for the planetary nebulæ, how is it that we do not find them on the sites of well-known outbursts in the past ?

Tycho Brahé's great nova of 1572, which equalled Venus in brightness, was situated in Cassiopeia in declination 61° and about one and a half degrees from ϰ, according to his observations, which were taken with great care. After allowing for precession, we can determine the locality of the outburst to-day, but although a search has been made, there is no trace of a planetary nebula within 8° of it. Tycho Brahé's nova was not the first in this region, for two others were reported in old chronicles in the region between Cassiopeia and Cepheus. One occurred in A.D. 945 and another in A.D. 1264. There is, however, a very unusual type of planetary in R.A. $23^h 16^m$, Dec. +60° 39′ (Fig. 3), lying about 8° away from the site of Tycho's nova, and it may be that this is the result of one of the earlier outbursts. It differs from all other planetaries in the fact that the bright illumination of the clearly defined outline over about 80° of arc is due, not to a central star, but to an eighth magnitude star probably outside the shell altogether. The contour of the rest of the disk, which is only visible in part, is about 3′ in diameter, which at a distance of 200 light years would represent 0·3 of a light year in diameter.

It would seem that if the radiation from the central star falls below a certain temperature, and no longer extends into the ultra-violet, the whole nebular shell disappears, so far as visibility is concerned. This is only what we might have expected, but we are still left with the difficulty of explaining its continued existence at all as a shell of gas, if the spheroidal form is the result of a balance between gravitation and radiation pressure, the basis of most of the theoretical work on the subject. It is possible of course that it is no longer entirely gaseous, as there is some evidence of obscuration. This unique object at any rate shows us that there may be invisible as well as visible planetaries.

The researches of Keeler, Campbell, Moore, Wright and Curtis at the Lick Observatory on the planetaries were undoubtedly the most complete ever undertaken at a single observatory. Besides the direct photography with the 36-in. Crossley reflector, and the work with the slitless spectrograph, a spectrograph with a slit and high dispersion attached to the 36-in. refractor revealed the fact that some of the planetaries were still in motion radially, and also in slow rotation.

With the slit placed across the major axis when the outline was elliptical, the lines at λλ 5007 and 4959 were found to be either doubled or widened in the middle, and the ends of lines were slightly twisted in some cases. This doubling or broadening of the lines is naturally interpreted to-day as a measure of expansion or contraction, although Campbell did not agree with this view, but the twisting and inclination of the lines he explained himself as a rotation effect.

The most striking feature of the *O* type nuclear stars is their great and increasing intensity towards the ultra-violet end of the spectrum. The maximum radiation seems to be actually beyond the atmospheric limit of λ 2800, while the visual range is unusually faint. This explains why the central stars were missed in the days of visual observation, and why they come out so readily in photographs. Instead of colour excess, such as we find in the stars involved in the clouds, we find a large colour deficiency. It is difficult to give a reason for this faintness of the visual spectrum. It can scarcely be actual and we are led to think that there must be some physical effect in the mechanism of excitation of the gaseous shell which weakens the transmission of the longer wave-lengths but allows the ultra-violet to pass without loss of energy.