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INTERFEROMETRY OF THE MEDUSA NEBULA A21 (YM 29)

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The nebula A21 has been observed with a high-contrast Fabry–Perot etalon and a contact electronic image converter in the 6584- and 6563-Å lines. The model best satisfying the observations is a thin prolate-ellipsoidal shell inclined 50° ± 15° to the plane of the sky; its axial ratio is 0.4 ± 0.2, and its thickness is no more than 0.3 of its mean radius. The mean radial velocity of the nebula as a whole is + 24 ± 5 km/sec relative to the Local Standard of Rest. The shell is found to be expanding at a velocity of 53 ± 10 km/sec. With this expansion velocity the nebula cannot be a supernova remnant, a result consistent with the radio observations.

The filamentary nebula A21 [YM 29 (Yerkes/McDonald), the "Medusa"] was discovered in 1955 by Abell [1], who classified it as an old planetary nebula, and independently by Johnson [2]. Abell estimated the size of the object as 744" × 509"; he has also obtained photoelectric U, B, V magnitudes for the central blue star ($V = 15^{m}.99$, $B-V = -0^{m}.32$, $U-B = -1^{m}.26$) [3]. Subsequently Minkowski [4] and Vorontsov-Vel'yaminov [5] interpreted the nebula as a possible supernova remnant analogous to the Cygnus Loop.

In 1971 Johnson and Rubin detected a weak source at frequencies of 1400 and 5010 MHz, which they have identified with A21 [6]. However, these observations have not provided a definite indication of the character of the radio spectrum. The radio flux density measured at 5010 MHz was found to be 10 times lower than the value obtained by estimating the integrated brightness of the object on the red Palomar Sky Atlas print, assuming that A21 emits negligible radiation in the [N II] lines. This circumstance compelled Johnson and Rubin to conclude that the object is peculiar. Further observations of A21 at frequencies of 318 and 606 MHz [7] have shown that the radio emission of the nebula is thermal in character, and that the object in all likelihood is a planetary nebula.

The first spectrograms obtained by Johnson [6] revealed only the [O II] doublet. The intensity ratio of the lines corresponded to N_e = 200-700 cm^{-3} for $T_e = 10^4$ °K. Later observations in the range 4200-7000 Å have permitted detection of the Hβ line; [O III]; unresolved Hα, [N II]; the unresolved [S II] doublet; and possibly λ 5876 He I [8]. The ratio $I_{[N\ II]}/I_{H\alpha} = 2$ that has been quoted [8] partially explains the disparity between the radio flux and the integrated brightness of the nebula in the Hα line. If one takes into account the high intensity of the [N II] lines, the observed and expected radio flux densities differ by a factor of not 10 but only 2 [8]. In October 1971, Esipov obtained a spectrogram of the nebula, using a grating spectrograph and an electronic image tube mounted at the Cassegrain focus of the 125-cm reflector [9]. In the observed region of the nebula $I_{[N\ II]}/I_{H\alpha}$=4-5, which completely removes the discrepancy reported [6] between the observed radio flux density of A21 and that estimated from $I_{H\alpha}$. This finding provides independent evidence for regarding A21 as a thermal radio source.

TABLE 1

	$I_{[O\ III]}/I_{H\beta}$	$I_{[S\ II]}/I_{H\alpha}$	$I_{[N\ II]}/I_{H\alpha}$
Simeiz 22	3.8 [9]	0.9 [9]	5.0 [9]
A 21	4.2 [8]	0.6 [8]	2.0 [8] 4–5

On the other hand, the results of the spectroscopic observations do not permit one to regard the excitation of the line emission as purely radiative for T_e = 10,000-20,000°K. The observed intensity ratios of the forbidden lines to the hydrogen lines and the Balmer decrement indicate either a higher value of T_e (which would agree with the abnormally blue color of the central star) or that the line emission is collisionally excited [8]. In fact, a comparison of the optical spectra of A21 and the type I supernova remnant S22 shows that they are completely identical (see Table 1).

To investigate further the physical conditions in the nebula, we carried out a series of interferometric observations of A21 in the autumn of 1971. The main purpose of these observations was to study the internal motions in the nebula. The observations were made with a Fabry–Perot interferometer equipped with a contact electronic image converter having a multialkali photocathode; this assembly was attached to the Cassegrain focus of the 125-cm reflector at the Southern Station of the Shternberg Astronomical Institute.

The high intensity of the [N II] lines permits investigation of the internal motions in the nebula at λ 6584 Å.

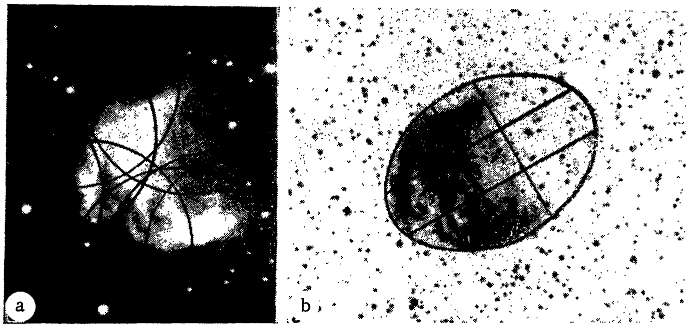

Fig. 1. a) Positive photograph of A21 taken through an interference filter centered on the 6584-Å line, showing the position of the 6584-Å interference fringes; b) negative print from the Palomar Sky Atlas, showing the strips along the axes of an ellipse within which the radial-velocity distribution of the filaments has been derived.

And although the lack of a laboratory source of [N II] radiation prevents an absolute determination of the radial velocities, relative velocity measurements and the construction of the line profile can be carried out with the same accuracy as in the Hα line. When investigating large-scale nebular motions it is in fact advisable to use λ 6584 rather than the Hα line, since the Doppler width of the former line, determined by purely thermal motions, is considerably smaller.

In a previous paper [10] we have given a detailed description of the techniques used in our interferometry program. Observations were made in the [N II] line with a Fabry–Perot etalon having coated plates with 96% reflectivity assembled on 0.15-mm separators. In the working region of the interference pattern the linear dispersion was 5-10 Å/mm, the actual spectral resolution 20-25 km/sec, and the space resolution 10-15". Exposures of 45 min were recorded on sensitized Kodak 103a-D emulsion. To allow for the nonuniform brightness of the nebula, direct photographs of A21 were taken through a filter of 35-Å half-width centered on the 6584-Å line. Altogether nine interferograms covering the nebula in a uniform manner were obtained and reduced.

Figure 1a shows the location of the [N II] interference fringes on a picture of the nebula. Radial photometric cross sections of the interference fringes were derived with an MF-4 recording microphotometer. Laboratory marks representing the Hα line were employed to correct for instrumental profile and to determine the velocity scale. Figure 2 displays several interferograms of A21. The central spot and the four marks around the edge of the interference pattern represent the laboratory Hα line; the ring between them, the 6584-Å line emitted by the nebula. These patterns show that in the central parts of A21 the spectral profile of the line is doubled, while at the periphery of the nebula it is narrow and single. Thus our first interferograms have established that the nebula A21 comprises a thin expanding shell.

To determine the expansion velocity we have examined the distribution of the radial velocity of individual filaments with respect to their distance from the center of the nebula. Overexposed photographs of A21 exhibit very faint filaments in the northwestern portion, filling the image of the nebula out to a regular ellipse of eccentricity 0.7 (see Fig. 1b). As a three-dimensional model for the nebula we have adopted a prolate ellipsoid of revolution, since that is the shape most justifiable physically (preferential ejection of material in two opposite directions, or expansion in a strong regular magnetic field). The orientation of the nebula in space is unknown, so that in order to estimate the angle by which the major axis of the ellipsoid is inclined to the plane of the sky we have sought to identify a characteristic asymmetry in the radial-velocity distribution of filaments aligned along the major axis of the projected image. Two strips have been marked out on the image

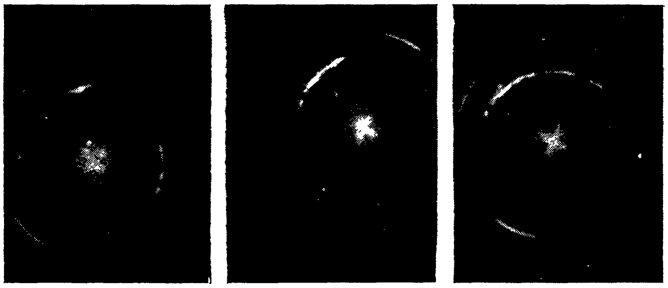

Fig. 2. Interferograms for A21. The features at the center and edge of the interference pattern represent a laboratory Hα line; the feature in-between corresponds to the 6584-Å line emitted by the nebula.

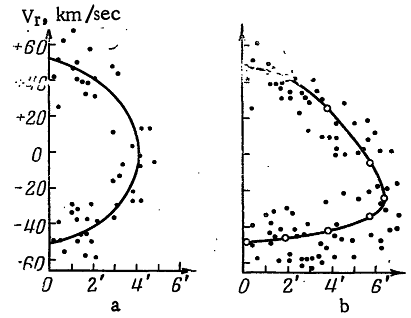

Fig. 3. Distribution of radial velocities of filaments with their distance from the center of the nebula. a) Filaments aligned along the minor axis of the ellipse (Fig. 1b); b) filaments aligned along the major axis. The solid curves have been computed for the radial-velocity distribution corresponding to an ellipsoid inclined by 45° to the plane of projection and expanding at a velocity of 53 km/sec.

of the nebula, along the major and minor axes of the ellipse (Fig. 1b), and the radial velocities of filaments situated within these strips have been considered separately.

In Fig. 3 we show the radial-velocity distributions of individual filaments as a function of distance from the center of the nebula in the plane of projection, derived from an analysis of the observations. Figure 3a corresponds to filaments aligned along the minor axis of the ellipse; Fig. 3b, to filaments aligned along the major axis. Relative radial velocities have been determined; in Fig. 3a the axis of symmetry has been taken as the origin of the velocity scale. Figure 3b, however, shows a definite asymmetry in the velocity distribution of filaments located on the approaching and receding sides of the envelope, implying that the major axis of the ellipsoid is strongly inclined to the plane of the sky.

To determine the angle of inclination we have calculated the distributions of radial velocity with distance from the center to be expected for points located on the major projected axis of an ellipsoid inclined to the plane of projection at different angles. Angles at 15° intervals from 0° to 90° have been considered. Since we do not know whether the expansion velocity is constant over the entire envelope, calculations have been performed for two cases: 1) The expansion velocity is independent of the location of the point upon the surface of the ellipsoid; 2) the expansion velocity is proportional to the radius vector of the observed point on the surface of the ellipsoid. Best agreement with the observations is obtained for inclination angles of 45-60° (with the southeastern part of the nebula located closer to the observer than the northwestern part). Evidently the expansion velocity does not vary appreciably over the envelope, as better agreement with observation is obtained for the case of constant velocity than for a velocity proportional to the radius of the envelope. The large scatter in the radial velocities of the filaments prevents us from obtaining a more accurate value for the inclination angle of the ellipsoid relative to the plane of the sky, or determining the law of variation in expansion velocity over the envelope.

The average expansion velocity derived from the data shown in Figs. 3 is 53± 10 km/sec.

Figure 3 includes the theoretical curves corresponding to the radial-velocity distribution of points located on the minor and major projected axes of an ellipsoid inclined by 45° to the plane of the sky and having a constant expansion velocity of 53 km/sec.

That the nebula has a shell structure is demonstrated at once by the interferograms of A21. Knowing the approximate orientation of the object, its shape, and its expansion velocity, we can determine the half-width of the [N II] line emitted at the edge of the nebula, and thereby estimate the thickness of the emission region. The mean half-width of the 6584-Å line radiated at limb points of A21 where splitting of the line is no longer observed is 45 ± 5 km/sec. This value merely provides us with an upper limit on the thickness of the envelope radiating in [N II], since it does not take into account the influence of turbulent motions that broaden the line. For the model and expansion velocity of A21 adopted above, we obtain $\Delta r/r \leq 0.3$ for the ratio of the thickness of the envelope to its radius.

To determine the radial velocity of the nebula A21 as a whole, an interferogram of the object has been obtained in the Hα line. The mean radial velocity of A21 is + 24 ± 5 km/sec relative to the Local Standard of Rest (or + 40 ± 5 km/sec relative to the sun), in full agreement with the value of [8].

Thus our investigation of the radial-velocity distribution and the half-width of the line profile has yielded the following parameters for the nebula A21: The nebula has a well-defined shell structure in the [N II] line, with $\Delta r/r \leq 0.3$; 2) the three-dimensional model for the nebula best satisfying the observations is a prolate ellipsoid of revolution whose major axis is inclined to the plane of the sky by an angle of 50° ± 15° with the southeastern end closest to the observer, and with an axial ratio of 0.4 ± 0.2; 3) the expansion velocity of the nebula is 53 ± 10 km/sec; 4) the mean radial velocity of the object as a whole is + 24 ± 5 km/sec relative to the Local Standard of Rest, in agreement with [8].

Generally speaking, expansion velocities of the order of 50 km/sec are encountered both in planetary nebulae and in decelerating supernova remnants. However, in the case of the nebula A21 the value we have obtained for the expansion velocity immediately excludes any identification with a possible type II supernova outburst. In fact, if we apply the relation between the linear size of the envelope and the expansion velocity as determined from the familiar type II supernova remnants Cassiopeia A, IC 443, the Cygnus Loop, and the Monoceros nebula [11], we find that the linear radius of A21 would be 20-30 pc. The corresponding distance to the object would be 7-10 kpc, which in the direction $l^{\mathrm{II}} = 205°$ would place it beyond the Galaxy. Its height of 1.5-2 kpc ($b^{\mathrm{II}} = 14°$) above the galactic plane would definitely be too great for type II supernovae. In the case of a type I supernova, on the other hand, if we take an expansion velocity of 50 km/sec then the linear radius would be 4 pc, the distance 1-1.5 kpc (which, in general, would be consistent with our radial-velocity determination of + 24 km/sec), and the height above the galactic plane 200-400 pc. Thus if we identify the nebula A21 with the remnant of a type I supernova outburst, it would represent an object analogous to S22 in size, expansion velocity, optical spectrum, and morphology.

However, the most important criterion, the thermal character of the radio emission, compels us to regard A21 as a planetary nebula [7]. In this event, according to Abell's estimate [3], the distance to A21 would be 180 pc, and the radius of the object, 0.3 pc. In view of the shell structure of the source, if we suppose that the filaments occupy 0.01 of the thickness of the envelope and take $N_e = 200\text{-}700\ \mathrm{cm}^{-3}$ we can obtain a rough estimate for the emission measure EM in the nebula. For the case of a planetary nebula we have EM = 10^2-10^3; for a type I supernova remnant, EM = 10^3-10^4. The radio observations [7] and the estimated brightness of the nebula in the Hα line yield EM $\approx$ 500. Thus the value we have derived for the expansion velocity provides new evidence that A21 is a planetary nebula. It would not be worthwhile to obtain optical spectra of the nebula and of the central blue star at high dispersion.

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