

LARGE NEBULAR COMPLEXES IN THE NORTHERN
PORTION OF THE GALAXY

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Abstract

Several northern complexes of ionized hydrogen, stars and possibly non-thermal radio emission are known whose properties are similar to those of Gum's nebula. Among the best known complexes are the Ori I and Ceph IV associations and IC 1795-IC 1805-IC 1848. Each of these complexes contains an extended ring structure and requires more excitation than is available from the known early-type stars. We examine the properties of these objects and show that many of the properties of Gum's nebula are common to such galactic complexes.

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Introduction

Several of the better known nebular complexes have properties reminiscent of those ascribed to Gum's nebula by Brandt *et al.* (1971). Although none of the complexes we consider contains pulsars (Reifenstein, Brundage and Staelin 1969), four of them have nonthermal emission associated (Ori I, Ceph IV, W28, Monoceros). All (except W49) contain a low-surface-brightness ring structure surrounding a central star clustering. In these cases where a significant portion of the exciting stars can be identified (Ori I, Ceph IV, IC 1805), the stellar component is visible through the ring and may have dense H II associated with the stars (Ori I) or the individual stars may be highly reddened as if they were surrounded by dust clouds (Ceph IV; Reddish 1967). In any case, the dust distribution is highly irregular throughout the complexes.

The volume occupied by these complexes is larger than the typical H II regions studied by many observers (for example, Schraml and Mezger 1969). This can be attributed to the relatively extended associations which are responsible for at least part of the excitation of the nebulosities. In each case, a substantial amount of neutral hydrogen, ionized hydrogen, dust and molecules is scattered throughout the volume. Such data as are available indicate that each of these components is highly clumped. The gas and dust mass can be of the order of $10^4 M_{\odot}$, while each of the complexes contains at least $10^2 M_{\odot}$ in stars.

In the following sections we will examine the data on each of these complexes. The available radio data will be stressed since the radio brightness is unaffected by optical absorption. In the final section we will compare these objects and Gum's nebula.

The Orion I Association

The Orion I association contains several stellar groupings of a common origin but with different ages (Blaauw 1964). The youngest of these stellar groupings contains the stars responsible for the excitation of the Orion Nebula (M 42, M 43). In addition to the bright nebulosity around the Trapezium, bright nebulosity is associated with λ Orionis and the ζ Orionis region (NGC 2024, and IC434; it is unlikely that ζ Ori excites NGC 2024, M. A. Gordon 1969). Beside these bright nebulae, weak nebular emission pervades most of the region between the dense H II regions and dust clouds are present throughout. The most obvious dust clouds are the dark bay which enters M 42 on the east side and reaches almost to the Trapezium, the dark cloud which divides NGC 2024 into roughly equal parts and the dark bay associated with the Horsehead Nebula. A number of early type stars are scattered throughout the region (Walker 1969).

The extent of the stars and nebulosity of the Ori I association is best seen on very wide field, long exposure photographs. From these photographs (see, for example, the frontispiece to Baker's Astronomy) it is clear that the nebulosity covers the whole constellation and extends northward until it merges with the Milky Way in Gemini. A conservative estimate of the projected size is an ellipse with axes $40^\circ \times 30^\circ$ with the major axis at position angle 30° . Within these boundaries, a number of extended structures can be seen. The brighter of these structures are associated with the Barnard Loop. In red light, the Barnard Loop appears to be an ellipse of axes $14^\circ \times 10^\circ$ with the major axis at position angle 0° and centered roughly between the Sword and Belt regions of Orion.

Using Gemini-11 ultraviolet objective prism photographs, O'Dell, York and Henize (1967) showed that the Barnard Loop is extremely bright at short wavelengths. They suggested that the Barnard Loop represents the interface between predominantly ionized hydrogen and predominantly neutral hydrogen in the outskirts of the Ori I association. On this hypothesis, the Barnard Loop is the result of the interaction between the stellar radiation field and the gas and dust from which the stars of the association formed. It appears that, if the Barnard Loop is radiatively excited, some Lyman continuum flux must leak through, since material beyond the Barnard Loop is ionized. The optical emission measure, however, is probably less than 600 because of the very low surface brightness. Because of the great extent of this low surface brightness component, a substantial source of energy is required to maintain it.

Continuum interferometry of the compact nebulosities (M 42, M 43, NGC 2024, etc.) shows that each contains considerable structure on a size scale of 10 arc sec (0.03 pc). These structures have been interpreted as the ionized remnants of the protostar complexes from which the exciting stars formed (Webster, and Altenhoff 1970a; Wink, Webster, and Altenhoff 1971). Each of the compact nebulosities is surrounded by a less compact envelope which gradually merges into the surrounding background. Thus, the compact nebulae are core-halo sources (cf.: Schraml and Mezger 1969). At centimeter wavelengths, only the most dense nebulosity can be detected without difficulty in continuum measurements. To detect the least dense portions of the nebulosity, high sensitivity and low frequencies are required.

Rishbeth (1958a), has mapped the Orion complex at 85.5 MHz and 19.7 MHz using Mills Cross antennas. The half-power responses were $50' \times 60'$ and $85' \times 100'$ respectively. In addition to emission from the stronger sources, Rishbeth detected 85.5 MHz radiation which is clearly associated with the Barnard Loop. This radiation comes from a rough ring less than 15 pc thick with an electron density of about 4 cm^{-3} on the eastern side and $\leq 1.5 \text{ cm}^{-3}$ in the faintest portions of the ring. A diffuse source about $7^\circ \times 12^\circ$ in extent covers most of the Barnard Loop but extends beyond the northeast portion of the Loop

(this object is called Orion X by Rishbeth). Since absorption from this diffuse source is not detected at 19.7 MHz, Rishbeth infers that the source might be nonthermal. This important observation needs confirmation. Should the interpretation prove correct, it suggests that a supernova might have occurred in the heart of the Ori I association a long time ago. If the source is thermal, however, its emission measure is $\leq 300 \text{ pc cm}^{-6}$.

Observations of the central portion of the association in the 21-cm hydrogen line (C.P. Gordon 1970) show that a considerable amount of neutral hydrogen is present ($7 \times 10^4 M_{\odot}$). The central region is clearly recognizable on velocity-longitude plots because of its apparent rotation with respect to the surrounding gas (period $\sim 5 \times 10^7 \text{ yr}$). The center of the Barnard Loop is not coincident with the area of increased H I density which could be said to define the center of the complex. The Loop center is more than 3° from the peak of the H I and the Loop is wholly contained in the H I region bounded by the rotation. It is of considerable interest that radio recombination line observations of M 42 (Mezger and Ellis 1968) and NGC 2024 (M. A. Gordon 1969) indicate a rotation of the ionized gas in the opposite sense from the neutral gas.

The presence of considerable optical absorption is implied by the many dust clouds and reflection nebulae within the complex. Further, the 21-cm emission studies (C. P. Gordon 1970) and interferometric studies of the 21-cm absorption (Clark 1965) show that the hydrogen is highly clumped.

From these data, a picture of the Ori I association emerges. Within a volume whose projection is an ellipse with axes of at least $350 \text{ pc} \times 260 \text{ pc}$, is a vast complex of gas, dust and stars. The highest surface brightness objects in the complex are high density, highly clumped H II regions. These objects are typically 2 pc in diameter and contain a few M_{\odot} of ionized gas and as much as $100 M_{\odot}$ in stars. Surrounding these high density regions and their more diffuse halos is a ring of nebulosity with axes $100 \times 80 \text{ pc}$. Underlying these structures is a very diffuse low-frequency radio source which may either be very thin plasma or nonthermal emission. The amount of neutral hydrogen and dust and the clumpiness of the distribution suggests that the period of star formation is not over in the Ori I association.

The Cepheus IV Association

The optical structure of the Cepheus IV OB association has been studied extensively by MacConnell (1968). He found that it contains numerous T-Tauri stars and reflection nebulae and a substantial number of O and early B stars. The central portion of the association is obscured by a dust cloud which appears to have a fairly sharp edge. Bright rims occur on the southern edge of the cloud.

The inner part of the association is surrounded by an irregular ring of emission nebulosity (NGC 7822) of diameter about 2° . The brightest portion of the ring is on the southern side, near the edge of the dust cloud, so that some sections of the ring are seen through the dust cloud.

Radio continuum emission from NGC 7822 has been studied by Churchwell and Felli (1970). They find that, as might be expected, the brightest portions of the ring are the strongest radio sources. The dust cloud, thus, does not completely absorb the optical radiation from the ring in these regions. Since the radio contours follow the overall optical emission well in most regions, the net absorption is light, although clearly spotty. The 6-cm radio contours show a well defined minimum in the center of the ring. From a comparison of the brightness temperatures at 20 cm and 6 cm, Churchwell and Felli conclude that there is a nonthermal component contributing to the emission of the two bright regions which comprise the southern portion of the ring. They further conclude that the nonthermal component becomes increasingly important on the western side of this region. Although this conclusion can be disputed on the basis of the accuracy of the flux density and brightness temperature measurements, the available Lyman continuum flux is at least a factor of 2 less than that required by the assumption that the radio emission is wholly thermal.

MacConnell (1968) finds that the association has a diameter of 60 pc. On the basis of similar distances, he suggests that the Ceph I and Ceph III associations as well as the Ceph IV association might be part of a huge OB complex. The individual associations would be the Blaauw (1964) subgroups of the complex. Should this be true, the complex covers a region $24^\circ \times 10^\circ$ on the sky and extends over a line of sight distance of more than 130 pc, centered 800 pc from the sun.

The IC 1795 - IC 1805 - IC 1848 Complex

This large complex which contains the Cassiopeia OB VI association, covers a region at least $5^\circ \times 3^\circ$ on the sky and is about 3 kpc distant. It contains the radio sources W3, W4 and W5. W3 is a compact, high density H II region on the northwest edge of W4. W4 is an extended ring-like nebula which surrounds IC 1805, similar to NGC 7822 and Ceph IV (Akabane et al. 1967). W5 is associated with IC 1848 and S26. No evidence is available to suggest that any non-thermal emission comes from this complex (Caswell 1967).

W3 is associated with IC 1795. No exciting stars are known for all but the most diffuse portions of the object even though some of the brightest optical nebulosity of the entire complex occurs in this region. Thus, it is not surprising that single antenna (Schraml and Mezger 1969) and interferometer mapping (Webster and Altenhoff 1970b) show the presence of several small, extremely

dense condensations near the peak of radio emission while most of the radio source is obscured by at least 7 magnitudes of dust (Ishida and Kawajiri 1968). One of the optically invisible, compact sources is associated with strong OH and H₂O emission (Aikman 1969; Schraml and Mezger 1969).

The H-alpha isophotes of Ishida and Kawajiri (1968) show that IC 1795 is a bright region on the northeast portion of a ring of emission nearly 3° in diameter which surrounds the cluster IC 1805. The cluster contains several OB stars, the earliest being of spectral type O5V (Ishida 1970). The ring surrounding IC 1805 is roughly defined at radio wavelengths and shows a minimum in the center. Several bright condensations mark the border of the ring. None of these condensations is as bright as IC 1795, however.

To the east of the ring around IC 1805 is another ring structure associated with IC 1848 and S26. The ring is not very obvious on optical photographs because of substantial absorption of light from the northern portion of the nebula. At centimeter wavelengths, the ring structure is very clear and the central minimum is well defined (Kaifu and Morimoto 1969). The dust clouds probably obscure both the optical emission corresponding to W5 and the total extent of the entire complex.

Other Complexes

We have examined some of the best studied complexes. Other groupings may have similar properties. These merit additional study both in the radio and optical regions of the spectrum.

The complex W28 consists of a ring-type supernova remnant and two thermal sources. The nonthermal component is unique in that, although it has been identified as a supernova remnant (Goss and Robinson 1968), radio recombination line radiation has been detected from the brightest portion of the ring (Reifens et al. 1969).

W49 (Mezger, Schraml and Terzian 1967) is on the other side of the galactic nucleus from the sun at a distance of 14 kpc. Although the total extent of the thermal component can not be determined, the total excitation required to support the observed portion suggests that this component surrounds a very young association. More than 5 OB stars are needed in a volume of diameter 4 pc to account for the radio emission (Webster, Wink and Altenhoff 1971).

A recent study of the region of the Rosette nebula was made by Holden (1968) using a 178-MHz pencil beam array. The observations suggest that the Monoceros loop, which has been identified as a supernova remnant, may be

directly associated with the Rosette nebula. Should further observations support this suggestion, the complex would be comparable with the structure of the inner region of the Ori I association.

Discussion

Objects with many of the properties of Gum's nebula are rather common. In the past, such complexes have not been thought exceptional because of their size but rather due to the complexity of their structure and the diversity of their constituents. The angular size of Gum's nebula marks it as an exceptional object but it is not clear whether other complexes are as extensive. It may be that Gum's nebula is unique in that its outer portions can be traced optically to very low emission measures.

It should be noted that Gum called his nebula a "giant" H II region by virtue of its apparent size. More recently, "giant" H II regions have been characterized by the value of D^2S , where D is the distance, usually in kpc, and S is the flux density emitted by the entire source at a frequency where both the H II region and the intervening medium are optically thin. For a "giant" H II region, D^2S is required to be greater than some value, usually 400. Hjellming (1968) has shown that this parameter is a measure of the total Lyman continuum luminosity required for excitation of the observed radio emission. While each of the complexes we have discussed is a "giant" H II region by this criterion, the thermal portion of Gum's nebula is clearly not a giant H II region (see Rishbeth 1958b).

For most of the complexes we have discussed, the known sources of excitation are insufficient to account for the observed continuum radio emission by at least a factor of 2. Because of the extensive and irregular dust clouds associated with these complexes, it has been usual to ascribe the missing excitation to completely obscured O-stars. Some justification for this assertion is to be found in the fact that the overall spectral indices for the radio sources are thermal to within the errors of measurement.

Except for W49, the objects considered show a low surface brightness ring surrounding their inner parts. It is not clear in every case whether the rings can be explained by mechanisms connected with the early-type stars of the complexes or whether a primeval supernova explosion is required. Such evidence as is available suggests that the ring in W28 and the Monoceros loop are supernova remnants while the Barnard Loop, the Rosette nebula, W4 and W5 are thermal. Further work is required to settle the question for Orion X and NGC 7822. In the case of the clearly thermal rings, the areal extent of the associated surface brightness emission is large enough so that the required excitation must greatly exceed the excitation needed to sustain the emission of the denser regions.

The total angular size of these complexes is difficult to determine optically because of the associated dust clouds. The best hope seems to be low frequency, high sensitivity, high resolution radio observations. Since these observations detect the lowest density ionized material in emission, it might be possible to observe the ionized hydrogen of a complex almost to the density where it merges into the surrounding medium. It is, of course, important that the nonthermal foreground and background emission be properly accounted for. Some support for this suggestion comes from the work of Rishbeth (1958a), who detected 85 MHz emission from material in Ori I with emission measures as low as 300. Mills Cross antennas, because of their large collecting area and beam swinging capabilities seem ideal for this purpose.

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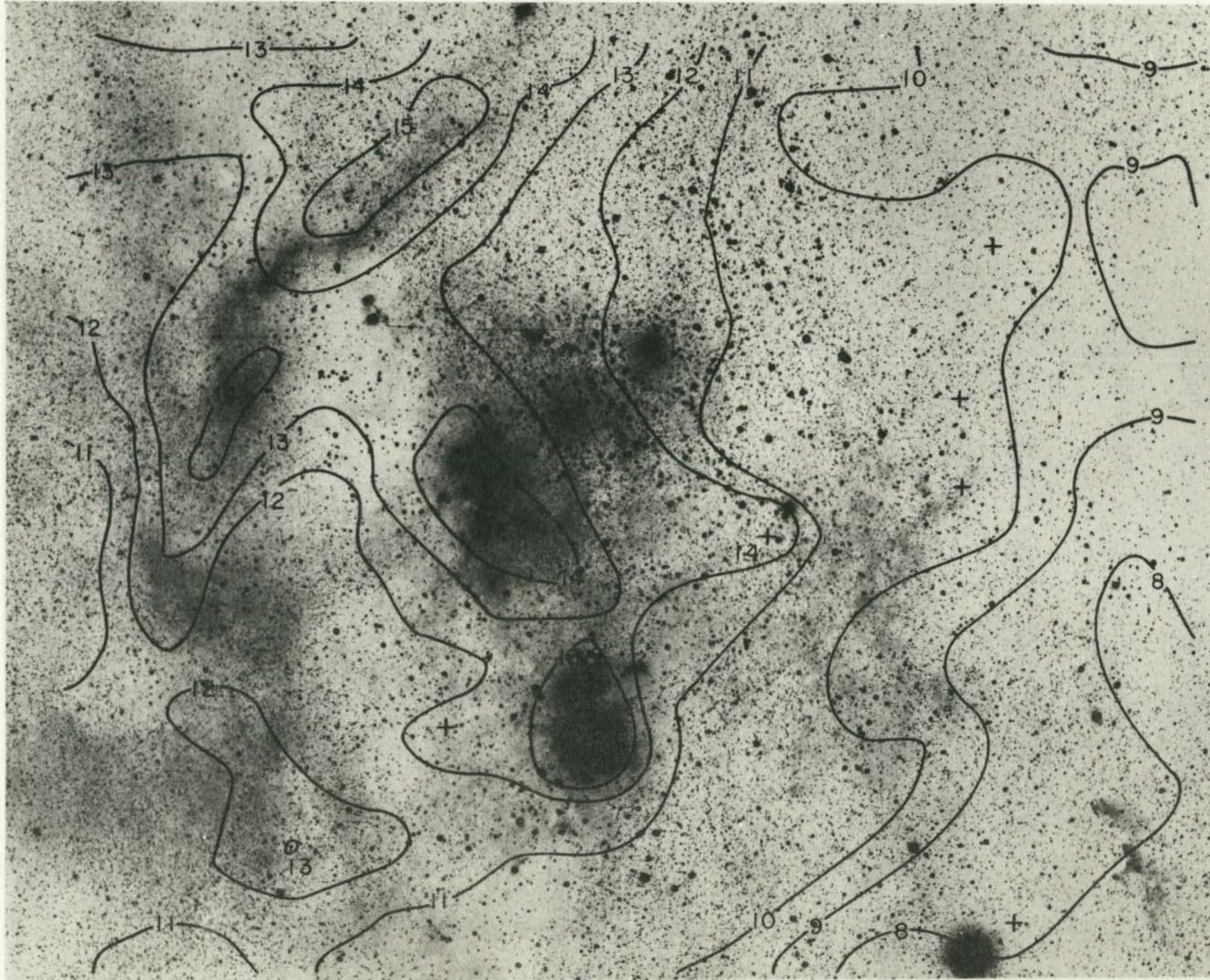


Figure 1. Overlay of Rishbeth's 3.5-m map of the radio emission from the inner regions of Ori I on a wide-field photograph. Contour unit = 100°K . + = unresolved source; \odot = extended source. Courtesy of R. M. Hjellming and C. S. Smith.