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A REMARKABLE FEATURE IN THE GIANT EXTRAGALACTIC H II REGION NGC 5471

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ABSTRACT

We report the discovery of a very high velocity, low-intensity gas feature in the giant extragalactic H II region NGC 5471. A broad component in the emission lines of Hα + [N II] λλ6548, 6584 is located within an area less than 1″ in diameter at the position known as knot C. The broad component is characterized by its low intensity (less than 2% of the peak surface brightness in Hα), a contribution of ≈25% to the total flux of the lines, and an extension of ≈3300 km s^{-1} at full width at zero intensity (FWZI). Supernovae explosions and stellar winds are considered as possible sources of the gas motions, and the observational evidence for their presence is discussed.

Subject headings: galaxies: individual (NGC 5471) — galaxies: interstellar matter — nebulae: H II regions — nebulae: internal motions

I. INTRODUCTION

Giant extragalactic H II regions (GEHRs) are the sites of active star formation, ionized by populous clusters of massive stars. Therefore, it is quite likely that an appreciable fraction of those stars have already evolved, making probable the existence of supernova remnants (SNRs) within the complexes (Richter and Rosa 1984; D'Odorico, Dopita, and Benvenuti 1980). The effects of the stellar winds from those massive stars and supernovae explosions must be taken into account when explaining the overall dynamical state of the gas. Both phenomena are associated with the existence of gas at high velocities (≈10^2–10^3 km s^{-1}), whose detection could be possible with the use of spectroscopic techniques. For instance, a kinematic approach for the detection of SNR has been used by Chu and Kennicutt (1986, hereafter CK) with the help of long-slit echelle spectroscopy. They were able to detect large velocity widths in Hα, at low intensity level, within NGC 5471 and 5461. Nevertheless, as pointed out by Vilchez *et al.* (1989), there could exist a danger of missing low-intensity gas at velocities of order several thousands of km s^{-1}, due to the moderate S/N and the limited free spectral range used. To overcome this problem, a possible alternative method of detection is the use of CCD detectors with long-slit intermediate resolution spectroscopy and long integration times. The combination of quantum efficiency, linearity, high signal-to-noise ratio, and spatial coverage should enable the detection of large-velocity/low-intensity gas within the regions.

To test this observational approach, and as a part of an ongoing program to study the kinematics and physical conditions of GEHRs, we have conducted a search for high-velocity gas in the five largest H II complexes in M 101 (NGC 5471, 5462, 5461, 5455, and 5447), which has resulted in the discovery of ionized gas at very high velocities within the NGC 5471 region. The following section describes the observational strategy and data reduction; the results and discussion are presented in § III, and our main conclusions are summarized in § IV.

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II. OBSERVATIONS

The instrumental configuration was optimized to provide maximum quantum efficiency of the system in order to search for possible faint components associated with the high-velocity gas in the regions studied. A suitable configuration for this program was available at the IDS Cassegrain spectrograph of the 2.5 m Isaac Newton Telescope at the Roque de los Muchachos Observatory, La Palma, Canary Islands.

The observations were performed on 1989 May 12/13 under subarcsec seeing conditions. The detector used was a GEC CCD of 578 × 385 pixel^2 with the 500 mm camera; the spectral dispersion attained was of 0.7 Å pixel^{-1}, giving a total spectral range of 400 Å, centered at Hα. A long-slit 180 μm wide (equivalent to 1″) was used, giving an effective resolution of 1.8 Å, as measured from the full width at half-intensity (FWHM) of the Cu/Ne arc lines. In the spatial direction the scale was 0.″33 pixel^{-1}. In the case of NGC 5471, the slit was oriented to cover the positions associated with the knots, defined by Skillman (1985), while for the chainlike regions (NGC 5461, 5462, and 5447), the slit was oriented along the main axis of the region. The typical total integration time was 1 hr.

In addition, IPCS (Image Photon Counting System) spectra were obtained for the regions NGC 5471 and 5461. The observations were made during 1986 April 13/14 with the same telescope. The IPCS was used with the 235 mm camera, in the configuration of 2040 spectral channels by 120 spatial increments, with a pixel size of 50 μm in the spatial direction and 15 μm in the spectral direction. A 300 grooves mm^{-1} grating was used, giving a dispersion of 137 Å mm^{-1}, over the spectral range from 3500 to 7000 Å, and an effective resolution better than 4 Å. Each spatial increment was equivalent to 0.″75.

With the use of the FIGARO software package, the two-dimensional spectra were bias and flat field corrected, all the cosmic-ray signals removed, reduced to absolute fluxes using standard stars, and wavelength calibrated. Full details of the observational set-up and the reduction procedure will be published in a forthcoming paper (Castañeda, Vilchez, and Copetti 1990).

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III. ANALYSIS AND DISCUSSION

With an angular extension of 35″, NGC 5471 is the largest and outermost GEHR of M101, and has been the subject of detailed studies; the work of Skillman (1985) is probably the best reference paper on the physical conditions of the nebula. Morphologically, the region presents five knots, surrounded by a faint halo and, following his convention, we have called them A, B, C, D, and E.

a) Search for High-Velocity Gas

To examine the line profiles along the slit, a series of one-dimensional spectra were extracted co-adding three rows ($\approx 1''$) from the CCD frame. Each spectrum was analyzed individually. The local electron density was derived from the [S II] $\lambda\lambda$6717, 6731 doublet ratio, solving a five-level atom with the values of the atomic parameters obtained from the compilation of Mendoza (1983).

Two kinds of peculiar emission profiles were found in the region: (1) a broadening only in the Hα line at low intensity, larger than what should be expected for a Gaussian profile (e.g., ≈ 600 km s^{-1} at knot B), as previously observed by CK, and (2) an underlying very broad component, with full width at zero intensity (FWZI) for Hα + the [N II] doublet of order thousands of km s^{-1}, detected at the position of knot C. To quantify the size of the broad emission-line region, a search was performed making several cuts along the spatial direction on the two-dimensional CCD frames. Wavelength windows of 2 Å were chosen in the ranges where emission from any high-velocity gas should appear; subsequently, equivalent spatial profiles corresponding to a pure nebular continuum were subtracted, and the resulting profiles were visually inspected. For those profiles showing "sources" of extra residual emission, over a 3 σ level, a Gaussian fitting was done, and its FWHM (after deconvolution by the seeing) was defined as the size of the region where the HVG was observed.

Figure 1*a* shows the low-intensity section of the calibrated spectra for Hα + [N II] $\lambda\lambda$6548, 6584 at knot C. The narrow Hα line has a FWHM of 37 km s^{-1} whereas the broad component has a FWZI of 3300 km s^{-1}. The flux of this broad component accounts for $\approx 25\%$ of the total flux of Hα plus the [N II] doublet. The size of the region where HVG is concentrated is ($0''.9 \pm 0''.2$), or (31 ± 7) pc (assuming a distance of 7.05 Mpc for M101; Rowan-Robinson 1988). The electron density at knot C is (85 ± 15) cm^{-3}. A red asymmetry on the line profiles of Hα and [N II] λ6584 is noticeable in the spectrum. These features have been marked as *A*, *B*, and *C* in Figure 1*a*.

We must emphasize that these features are observed in the three independent CCD integrations that included knot C. Figure 1*b* shows the IPCS spectra of knot C (*dashed lines*) normalized to peak surface brightness in Hα, compared with the CCD (*solid line*); even with a lower spectral resolution and quantum efficiency, the feature marked as *C* is also observed in the IPCS spectra. If that emission feature should correspond to Hα, it would imply a redshift of 1700 km s^{-1}. The [S II] lines do not show broad components as seen in the [N II] lines, even though the two ionization states have a similar ionization potential and the lines have similar peak surface brightness at that position. A possible explanation is that the high-velocity gas has a higher density so that the lines are collisionally de-excited.

A multiple Gaussian fitting was attempted of the profile of the narrow and broad components of Hα and the [N II] doublet. Assuming the simplest model, where each line is formed by a narrow and a broad component, an approximate fit is possible where the broad component has a FWHM of ≈ 600 km s^{-1}, the center of the line being redshifted by ~ 50 km s^{-1} (see Fig. 2) with respect to the velocity of the narrow component. The value of FWHM could be compatible with the order of magnitude of the velocities observed in 30 Doradus (Meaburn 1981), but the existence of wings as the one marked by C and the fact that the fit cannot adjust to the line profile suggest that the total motion of the gas is more complex than an expansion.

We have carried out a careful analysis to estimate possible instrumental and observational effects in the data. It is a well-known fact that some detectors produce wings at low-intensity levels. Due to our high S/N and our interest in detecting extended faint emission at low surface brightness, we tried to quantify the effect in our observational setup. By examination of narrow lines in H II regions and areas of NGC 5471, which

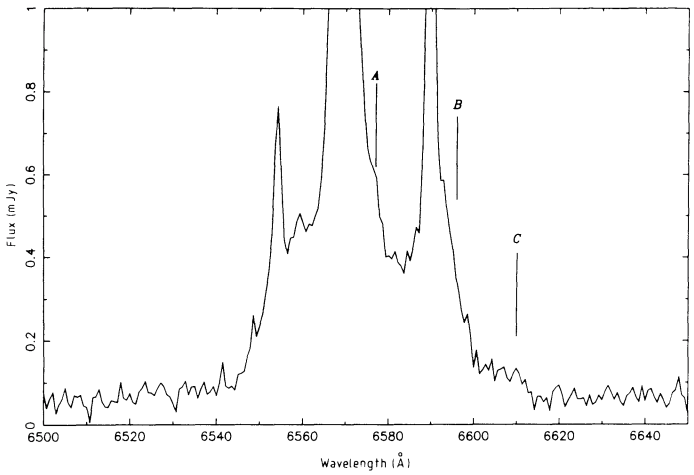

FIG. 1*a*

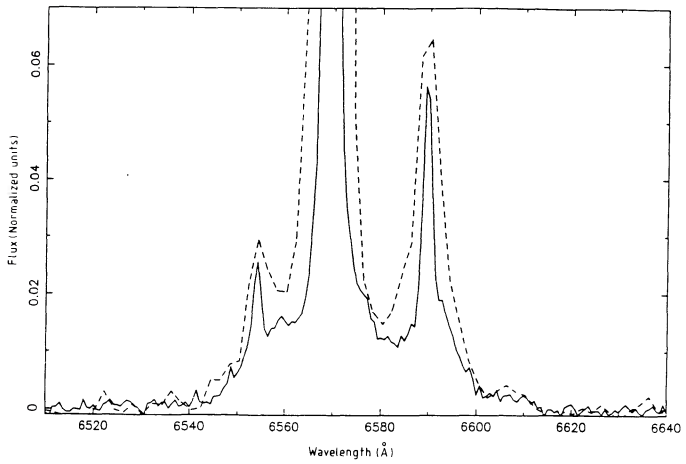

FIG. 1*b*

FIG. 1.—(*a*) Flux calibrated Hα + [N II] $\lambda\lambda$6548, 6584 emission profile of knot C in the region NGC 5471, for an area of $1'' \times 1''$. Notice the asymmetry of the emission profile of Hα and [N II] λ6583, indicated by the letters *A* and *B*, and the feature indicated by *C*. (*b*) Comparison of the spectra obtained by the CCD detector (*solid line*) and the IPCS (*dashed line*), both normalized to peak intensity in Hα.

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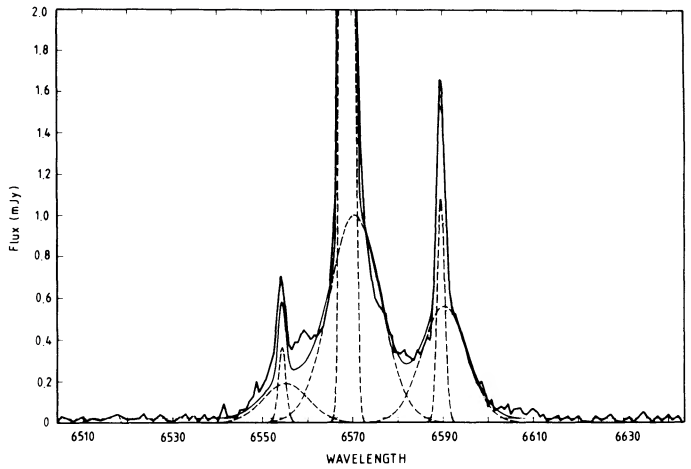

FIG. 2.—Gaussian fitting of the lines

we may define as normal regions and thus use them as controls, we estimated that the lines can be described as Gaussians, with a small departure from the Gaussian profile always below 0.5% of the peak of the line. To illustrate the difference between a "normal" emission spectra and knot C, we have plotted in Figure 3 the normalized line profiles at peak surface brightness of both the position of knot C and a position 1".5 to the NW of knot E. If problems such as imperfect illumination of the slit or instrumental profile asymmetries should exist, they would be revealed in those spectra, and this does not occur. The reproducibility of the observations is further confirmed by the similarity between the profiles obtained with the two detectors used.

b) Possible Sources of the Gas Motion

Supernova explosions and stellar winds have been proposed as the possible mechanism responsible of driving gas at very high velocities (see, for example, McCray and Snow 1979). We have attempted to ascertain the nature of the HVG detected, by examining all the observational evidence available for the presence of both phenomena in the region under study.

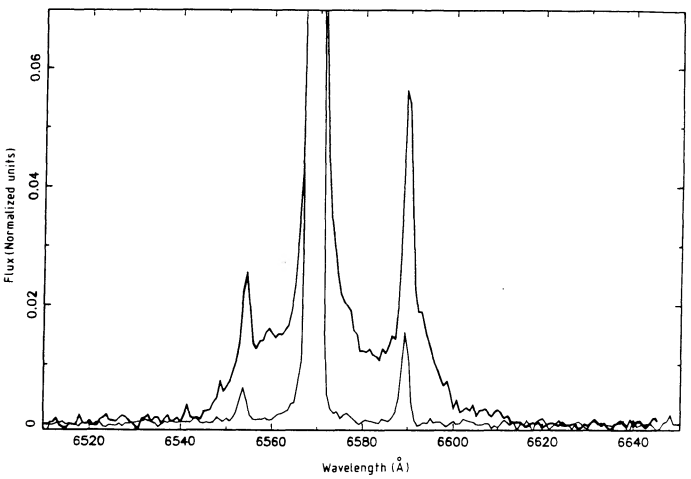

FIG. 3.—The Hα + [N II] λλ6548, 6584 emission profile (*solid line*) at the knot C compared with the "normal" emission for a zone in NGC 5471 1".5 to the NW of knot E (*thin line*). Both profiles are normalized to peak intensity in Hα.

There are three standard tests for detection of SNR in H II regions: the evidence of nonthermal radio emission, the strength of the [S II] line relative to Hα, and high gas temperature (Skillman and Balick 1984). Radio observations of the NGC 5471 region were taken by Sramek and Weedman (1986) using the VLA[4] at 1465 and 4885 MHz. They have shown that only knots A and B have nonthermal components (which scales to the number of supernova remnants) on the radio flux, with definitely negative spectral indices. For knot C, with a radio flux lower by a factor of 3 when compared with the other two knots, and a spectral index α zero, they did not detect nonthermal emission. But care should be taken when interpreting the value of the spectral index, since the thermal radio flux from the H II region could mask a faint nonthermal source, making the combined spectral index flatter (CK). As an example, we can estimate an upper limit in radio luminosity of a hypothetical SNR, taking as reference the error of 0.6 mJy in the radio flux at 20 cm quoted by Skillman (1985) for knot C, which translates to a luminosity of 3.4×10^{25} ergs s^{-1} Hz^{-1}, similar to the value given for Cas A (3×10^{25} ergs s^{-1} Hz^{-1}) by Cowan and Branch (1982), but an order of magnitude larger than the luminosity of the Crab (4×10^{24} ergs s^{-1} Hz^{-1}). Observational evidence for SNR comes also from spectroscopic observations, although the analysis of the spectra is difficult because of contamination by the underlying emission of the H II region. Spectrophotometry at intermediate (Skillman 1985) and high (CK) resolution appears to probe the likely existence of one (at knot B) and probably two more (knots A and C) SNR in NGC 5471. Indeed, our own IPCS and CCD data show the presence of stronger [O I] and [S II] in the spectrum of knot B, indicating the effect of collisional ionization. Moreover, the width of the [S II] lines is broadest at knot B (FWHM $\approx$ 115 km s^{-1}), as should be expected from a supernova shock wave excitation, while in knot C the width of the line is normal compared with a H II region. From the Gaussian fitting of the line profile, we have estimated the flux of the broad component in Hα to be of the order of 1.6×10^{-14} ergs cm^{-2} s^{-1} (corrected for $A_v = 0.7$ mag in the knot C, Skillman 1985). As a comparison, the Crab nebula would have a flux in Hα of 1.3×10^{-17} ergs cm^{-2} s^{-1} at the distance of M101 (Davidson 1987).

The red asymmetry in the emission lines provides an important clue about the kinematics of the gas. While supernova remnants may show asymmetric line profiles (see, for example, Chu and Kennicutt 1988), we rule out the possibility that the spectra could be similar to those expected by the effect of a collisionless shock (Chevalier, Kirshner, and Raymond 1980) in a young type I supernova remnant (Kirshner, Winkler, and Chevalier 1987). The model predicts a spectrum formed by two components at Hα, a narrow line and a broad one, without emission in [N II]. The asymmetry of the [N II] λ6584 line in our data indicates that the broad emission in hydrogen and nitrogen is associated with the same dynamical process.

A second physical scenario to be considered is the effect of stellar winds which come from the massive OB associations that ionize the regions (Snow and Morton 1976), or from the presence of Wolf-Rayet (W-R) stars, characterized by their strong mass loss ($\approx 10^{-5}$ $M_\odot$ yr^{-1}) and large terminal velocity ($> 10^3$ km s^{-1}) (D'Odorico and Rosa 1981; Conti and Massey

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1981). We searched for W-R emission in our IPCS spectra, in the bands of $\lambda\lambda$4580, 4730, and $\lambda\lambda$5750, 5780. Our results were in agreement with those from the survey of D'Odorico, Rosa, and Wampler (1983), but thanks to our spatial coverage we are able to detect those areas where W-R emission is present. Excess emission in the band $\lambda\lambda$4580, 4730 was found on the three brightest knots in NGC 5471 (A, B, and C), but we have not detected broad emission bands, which are characteristic of W-R spectra, at the position of the knot C (see also Skillman 1985). Only in the knot A does the S/N allow a fitting of the emission lines detected, which are clearly narrow.

There could be a possibility that part of the emission from the broad Hα component might be stellar in origin, but we believe that the observational evidence does not point out toward this prospect. In NGC 5461 for example, excess emission in the $\lambda\lambda$4500, 4850 region was detected in an area coincident in position and size with the stellar cluster (see Fig. 6*e* in the paper by Kennicutt and Chu 1988). An analysis of the spectra in that zone revealed very broad profiles of He II λ4686 (Rayo, Peimbert, and Torres-Peimbert 1982) with a FWHM of 1300 km s^{-1}, yet no broadening in Hα is detected there.

We conclude that there is not sufficient observational evidence to choose between the models of supernova remnants or stellar winds as possible sources for the high-velocity gas observed at knot C. As stated before, the detection of a SNR within a giant H II region is difficult because of the fact that the nonthermal radio continuum and the optical line emission are masked by the high surface brightness of the background H II region. On the other hand, the lack of W-R features in the spectrum of knot C does not provide conclusive evidence to rule out their existence, since as the lines are very broad and superposed to the stellar continuum, they are difficult to detect, unless the signal-to-noise ratio of the spectra is very high. It is interesting to note that the area where HVG is concentrated has a size comparable to the shells observed in NGC 604 by Rosa and D'Odorico (1982). This fact might suggest the existence of a compact cluster of massive stars similar to R136a in 30 Doradus (Weigelt and Baier 1985), giving rise to a wind-driven bubble (Weaver *et al.* 1977; Dyson 1979).

IV. CONCLUSIONS

The use of CCD detectors with long-slit intermediate dispersion spectroscopy and long integration times provides an excellent tool for the detection of very high velocity–low intensity wings (less than 2% of peak intensity) in the emission lines of GEHR.

With the use of that observational technique, we have been able to discover ionized gas with velocity one order of magnitude higher than the values previously detected within NGC 5471. Even with its low intensity, the gas represents an appreciable fraction (25%) of the total emission of the ionized gas at the position of knot C. Either stellar winds or supernova explosions are likely sources for the high-velocity gas, although there is no conclusive evidence of supernova remnants in the position where the phenomenon is observed, and moreover we have not detected the presence of Wolf-Rayet stars that could provide the energetic winds necessary to accelerate the gas.

In order to ascertain the true nature of the phenomena, the next logical step is to observe the lines of Hβ and [O III] with high S/N and high resolution. In this way, we could estimate the dynamical state of the ionized hydrogen. In addition, more radio observations at different wavelengths are necessary in order to confirm the lack of nonthermal emission from the source. Given the spatial scale of the phenomena, it would require observations with the *Hubble Space Telescope* to resolve the spatial nature of the source and to study its stellar population.

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