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NGC 6946: KINEMATICS OF THE STARBURST IN THE CIRCUM-NUCLEAR ZONE

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RESUMEN. Mediante observaciones espectroscópicas de relativamente alta resolución ($\Delta\lambda \sim 0.35$ Å) en la zona dentro de 30 segundos de arco del núcleo de NGC 6946 hemos detectado evidencia clara de expansión fuerte, con velocidades del orden de 100 km s^{-1}. Comparación de nuestros datos con mapas en intensidad de HI (21cm), H_2 (CO 2.6 mm) y de Hα sacados de la literatura nos ofrece un escenario de un brote de formación de estrellas, donde se hallan $\gtrsim 10^4$ estrellas OV. El gas, en la zona céntrica se ha consumido en gran parte en la formación estelar, mientras una nube de gas molecular placental sigue en posición alrededor del brote. La vida del brote se estima como 10^7 años por repartir el radio del orden de 1 kpc por una velocidad del orden de 75 km s^{-1}. En este tiempo y con un limite superior al ritmo de formación de estrellas de 10 $M_\odot$ año^{-1}, se puede consumir 10^8 $M_\odot$ de gas, que es menos de 10% de la masa de la nube molecular. Basado en nuestras observaciones proponemos un mecanismo para mantener el "starburst", usando la masa de moleculas en formación estelar progresiva.

ABSTRACT. Using spectroscopic observations at relatively high resolution ($\Delta\lambda \sim 0.35$ Å) in the region within 30 arcseconds of the nucleus of NGC 6946 we have found clear evidence of a strong expansion, with velocities of order 100 km s^{-1}. Comparison of our data with intensity maps in HI (21 cm) H_2 (CO 2.6 mm) and Hα taken from the literature we derive a picture of a starburst which contains $\gtrsim 10^4$ O5 stars. The gas in the most neutral region has been largely used in star formation, while a placental molecular cloud remains around the starburst. The lifetime of the present formation period is estimated at 10^7 years. In this time, with an upper limit to the star formation rate of 10 $M_\odot$ per year, a mass of 10^8 $M_\odot$ would have been used up. This is less than 10% of the mass of the placental cloud. We propose, based on our observations, a mechanism for maintaining the starburst, and using the molecular mass for progressive star formation.

Key words: GALAXIES-KINEMATICS AND DYNAMICS — STAR FORMATION

I. INTRODUCTION

The galaxy NGC 6946, a spiral of type ScI (Sandage and Tammann, 1974) is an object in which many supernovas have been detected (Minkowski, 1964; Barbon et al., 1982; Barbieri et al., 1982). From radio continuum studies by Van der Kruit et al. (1977), and an integrated H map by DeGioia-Eastwood et al (1984), one can derive an emission measure which corresponds to the presence of 10 05 stars in the zone within 30 arcseconds of the nucleus, which is a radius of 700 pc if the distance to the galaxy is 10.1 Mpc (Sandage and Tammann, 1974). Additionally measurements of the CO molecule via the J=1→0 transition at 2.6 mm wavelength, indicate the presence of molecular hydrogen gas, strongly concentrated in the circum-nuclear zone of the galaxy (Morris and Lo, 1978; Young and Scoville, 1982;

Ball et al., 1985), which affords a natural framework for a rapid rate of star formation. We have used our facility to obtain visible spectra of good spatial and spectral resolution to explore the physical conditions in the central region of the galaxy.

II. THE OBSERVATIONS

The observations were made at the Cassegrain focus of the 2.5m Isaac Newton Telescope of the Roque de los Muchachos Observatory, La Palma, Canary Islands. The spectrograph used was the IDS (Intermediate Dispersion Spectrograph) with a dispersion of 6.9 A mm , with the IPCS camera. The spectra covered a range of 500 Å centered on Hα, and included the emission doublet of NII at ~ 6570 Å, and the SII emission doublet at ~ 6700 Å. Our observations concentrated on the emission features from the HII regions in the observed zone.

The spectral resolution was 0.35 Å, limited by the slit width and not by the camera pixel size; we effectively used 2.2 pixels per resolution element, conforming to correct statistical practice. The linear range of the slit on the galaxy was 3.7 kpc, that is to say a field of radius 1.85 kpc centered on the nucleus. We chose position angles of 67°/247° and 157°/237°, corresponding to the major and minor axes respectively (Rogstad et al., 1973) and also interposed the angles 112° /292° and 202°/22°, thus effectively observing along 8 radii of length 1.85 kpc. The data were reduced using the STARLINK programme set, making specific use of the SPICA spectroscopic routines, at the Starlink nodes of University College, London and the Royal Greenwich Observatory. Wavelength calibration was via a CuAr arc, reduction employing a fifth order polynomial fit. The effective velocity resolution, when all pixel size, slit size and projection effects have been taken into account is 20 km s^{-1} .

III. VELOCITY CURVES

In Figure 1(a)-(d) we show the velocity curves derived from the doppler shift of H as a function of position along the slit at the four position angles cited. At first glance they seem to be normal "rotation curves", with a steady rise in velocity from the nucleus outwards. A more careful examination, however, reveals that the curve along the minor axis, and also that for position angle 112° , have slopes and velocity ranges much greater than those of the curve along the major axis.. As is well known, for a galaxy with purely rotational motion, the radial velocity curve along the minor axis should be completely flat, in other words with no measurable radial velocity component, rather akin to the curve we measure for NGC 6946 at position angle 202°. The apparent paradox in the present case has a natural explanation if we assume that the central region of NGC 6946 is in a state of expansion or collapse and that the vector velocity field is a projection of the superposition of radial motion onto a normal rotation field. The rotational velocity so near to the nucleus will not rise (for any Sc galaxy) above some 50 km s^{-1} at a galactocentric distance of 1 kpc, and the radial component here must reach values of 100 km s^{-1}.

In order to decide whether the radial motion is an expansion or collapse we turn to the CO spectrum of Young and Scoville (1982), taken with a beam diameter of 1.2 kpc, which is 50 arcseconds centred on the nucleus. The CO line has a large width of order 150 km s FWHM, with a rather square profile. The red wing is depressed compared to the blue, from which we infer more extinction in the red wing. This is the effect which would be predicted for an expanding emission region, and we may attribute the expansion to the physical effects of the O stars inferred to be present within the central zone. The same effect is reflected in the line profiles of our own sample, as explained below, serving to confirm the presence of expansion.

IV. Hα AND NII (λ 6584) PROFILES

In Figure 2 we compare the profiles of the Hα and NII (λ 6584) emission lines observed in the direction of the nucleus of the galaxy. Features to note are:

(i) The large widths of the lines: FWHM values of order 150 km s^{-1}.

(ii) The large splitting clearly visible in each line.

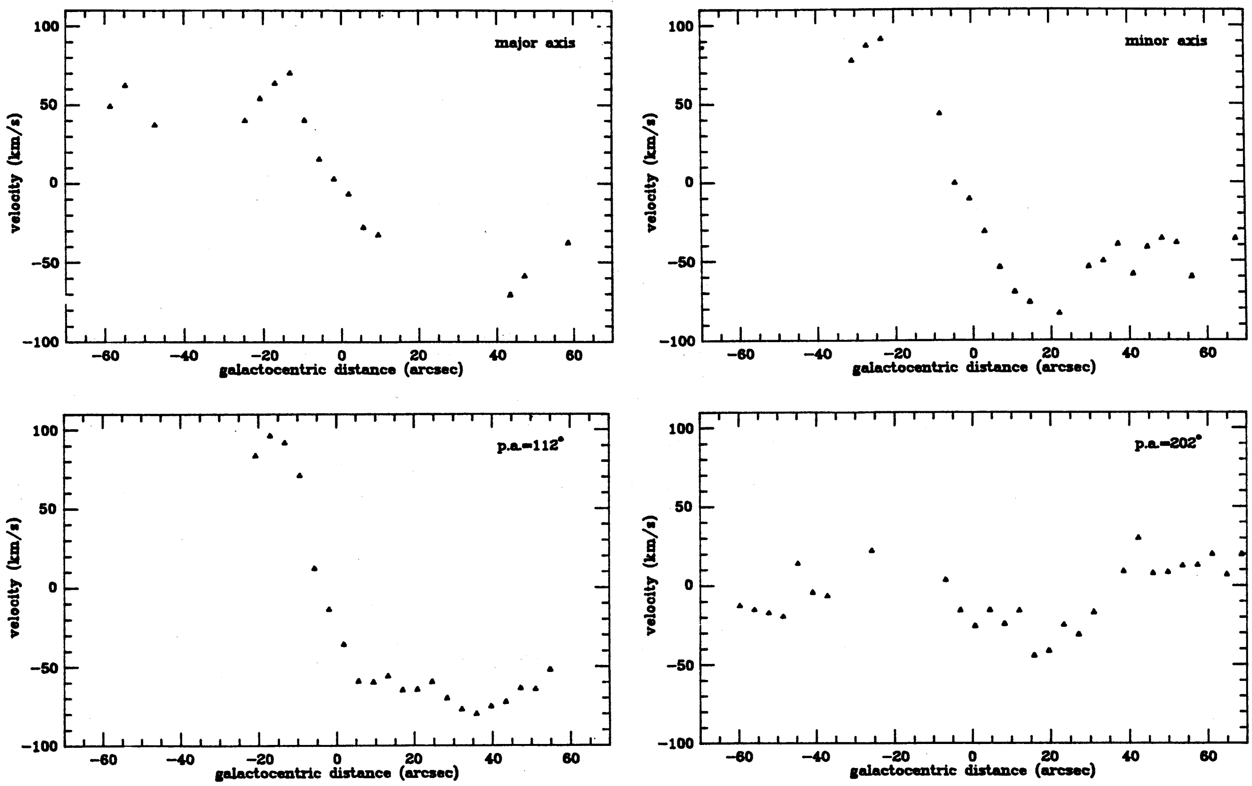

Fig. 1. Radial velocity curves for NGC 6946 along the axes indicated. 10 arcseconds corresponds to 240 pc at an assumed distance for NGC 6946 of 10.1 Mpc.

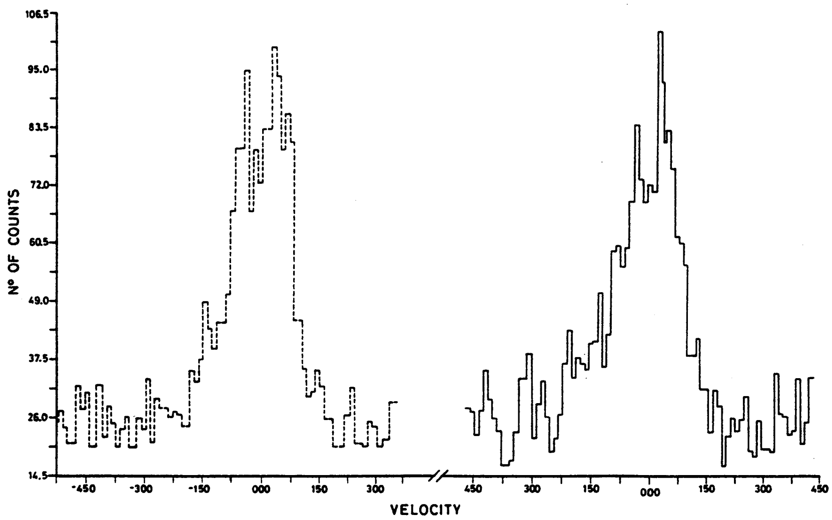

Fig. 2. Profiles of the Hα (solid line) and N II 6584 A (dashed line) in a 3 arcsecond section of slit (width 0.5 arcsec) centred on the nucleus of NGC 6946.

(iii) The asymmetry in the peaks, with the blue peak enhanced compared with the red in each line.
(iv) The profiles of both lines are remarkably similar.
(v) The non-gaussian forms of the lines, which have steep cut-away edges.

Without using space to show a large number of line profiles, we can summarize the changes which occur more or less symmetrically as the observed point moves away from the nucleus. Very rapidly one "half" of the line dies away, so that at 6 arcseconds from the centre, a typical line has a width of 70 km s^{-1}, without any splitting. In addition it has an asymmetric profile, with sharper fall-off to the blue at one side of the nucleus and to the red at the diametrically opposed side.

The simplest and most complete explanation of these observations is that the lines form in a thick shell of HII region material centred on the nucleus and expanding according to the velocity curves shown in the previous section. This explains the global profiles, but not the splittings. The latter must be due to the absence of emissive gas from the innermost sphere surrounding the nucleus. The central minima cannot be due to self-absorption because this would show up with either strikingly different shapes in the two lines, if the self-absorption were a pure scattering phenomenon or due to temperature gradients, or both. An absence of emissive gas from the centre of the expansion zone would, however, produce the congruent profiles seen. The absence itself could have two causes: the effect of the non-thermal source which has been detected by radio measurements in the central 3 arcseconds (Van der Kruit et al., 1977), which could completely ionize the hydrogen and nitrogen, or the use of all the central gas in star formation, given the initially higher density at the centre, which would lead to a higher star formation rate.

It is of considerable interest that the structures of both lines are consistent with a velocity field of the same form as that inferred above from the 4-axes velocity curves. Along the axis through the nucleus we are detecting this field with its radial velocity component "mapped" via the doppler effect, onto the emission profiles, with the central portion "eaten away" by absence of emission. From these profiles we can infer that the velocity field in the expansion zone is more or less spherically symmetric, i.e. with the velocity field along the line of sight having the same shape and amplitude as those in directions in the plane of the sky. It is not difficult to show that alternative models to account for the observed profiles: very high gas temperatures to try to explain the velocity widths, properties of single HII regions round individual super-hot stars (WR stars), a thin shell of excited expanding gas, are not able to explain the numerical values - especially the large line widths, but also the profiles and the form of the rapid radial variation.

V. SPATIAL AND TEMPORAL CONSTRAINTS ON THE STARBURST

It is instructive to compare our results with the distribution of molecular gas measured by Ball et al. (1985). They detected a CO distribution in the form of a bar, of dimensions 2.7 kpc x 550 parsec, with position angle 160°, that is to say along the minor axis, and centred near the nucleus. They estimate an H mass of 1.1×10^{9} $M_{\odot}$ which is in reasonable agreement with the previously estimated mass of Young and Scoville (1982) of 1.4×10^{9} $M_{\odot}$. Ball et al. suggest that the molecular "bar" should provide a mechanism for the transport of gas from the disc to the nucleus, but are not able to provide direct evidence for this in the form of a velocity field. They state that the detection of motions along the bar could not be distinguished from a rapid rotation curve. This conclusion is not justified, however, as we have shown here, and indicated in a previous article (Beckman et al., 1986) our Hα velocity data enable us to make exactly that distinction between radial and circular motions, and there is every reason to suppose that the CO lines can be used in a similar diagnostic manner.

Scoville and Young (1983) estimate the star formation rate in the central molecular cloud as 1.5 $M_{\odot}$ yr^{-1}, with the assumption that the rate is dominated by the stars which dominate the luminosity, i.e. the early type stars. With an initial mass function which is more correctly representative, i.e. that of Miller and Scalo (1979) the star formation rate is found by DeGioia-Eastwood et al. (1984) to be 7 $M_{\odot}$ yr^{-1}. Using an approximation of 5 M yr we can make an estimate of the gas used in forming stars up to now. The lifetime of the starburst can be estimated by taking an average expansion velocity of 50 km s^{-1}, and the size of the expansion zone as 0.5 kpc, which yields a time of $\sim10^{7}$ years. In that time some 5×10^{7} $M_{\odot}$ has been converted into stars. This value is an upper limit because it does not take account of the mass ejected into the interstellar medium by massive stars; the correction factor is, however, of order 10% and is not important for the present purpose of broad estimation. The figure tells us that we are probably at an early stage of the starburst, given the 10^9 $M_\odot$ in H_2 in the placental cloud. We are not sure if the star formation rate is tending to increase or decrease , and indeed there are plausible arguments in either direction. At all events, it is unlikely that the burst will last longer than 10^9 years, which implies a lifetime much less than that of the host galaxy.

Ball et al. (1985) propose a mechanism of gas flow along the bar towards the centre in order to maintain the starburst, and draw morphological parallels with IC342 (Lo, 1984). The model entails that the movement of the gas is in response to the gravitational potential of the bar, that the formation of a bar causes more star formation near its centre. Our present study suggests that whatever may be the velocity field of the bar there is another mechanism which can lead to an increased star formation rate which is positively dependent on the number of massive stars already formed. It is not possible to neglect the physical effects of the energy and momentum flux given out by the O stars in a starburst. These effects show themselves, in the case of NGC 6946, in the expansion and in the "clean-out" of the gas from the central 5 arcsecond sphere. We have calculated (Beckman et al., 1986) a momentum flux of 5×10^{43} kg m s^{-1} , and an energy flow into the expanding gas of 10^{34} watts, with a total kinetic energy of expansion of 3×10^{43} joules. The velocity of expansion, in the range up to 100 km s^{-1} can be compared with the velocity of sound in the molecular cloud. This is essentially H_2, and a generous upper limit to the temperature of 100 K yields a sound speed of 1 km s^{-1}. We are thus witnessing a prolonged shock wave, which will clearly be compressing the molecular gas. The starburst does not need to be "fed" from along the bar. Evolution of the burst can proceed outwards from the centre where it could have been initiated either by the presence of the non-thermal source, or more simply where the initial cloud density may well have been highest. This qualitative scenario is in broad agreement with what is known about the development of the central zones of "normal" galaxies, and can explain the phenomenon of "liners": low ionization nuclear emission line regions (Heckman, 1980; Keele, 1983).

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