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EXTENDED ROTATION CURVES OF HIGH-LUMINOSITY SPIRAL GALAXIES. V. NGC 1961, THE MOST MASSIVE SPIRAL KNOWN

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ABSTRACT

The rotation curve derived for NGC 1961 indicates a total mass greater than $10^{12}\,\mathfrak{M}_\odot$. This large value is confirmed by the correspondingly large mass, $>10^{11}\,\mathfrak{M}_\odot$, for the interstellar H I component derived from 21 cm measurements. This supergiant spiral has normal ratios formed from values of its total mass, H I content, and blue luminosity. The optically derived spectra indicate peculiar and unexplained motions within the system.

Subject headings: galaxies: individual — galaxies: internal motions — interstellar: matter — radio sources: 21 cm radiation

I. INTRODUCTION

NGC 1961 (Arp 184) is a pathological spiral galaxy which is classified SAB(rs)c (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) and SbPnt I: (van den Bergh 1960). Although at first glance it appears to be totally distorted outside of the nuclear regions, it can equally well be described as a generally normal spiral with long, straight, faint outer arms to the north and east of the nucleus, embedded in a confused dusty looping structure to the south and west. A reproduction of NGC 1961 kindly made available by Arp is shown in Figure 1 (Plate 1).

II. OBSERVATIONS

a) *Radio Data*

Neutral hydrogen measurements of NGC 1961 were made with the NRAO 300 foot (92 m) transit telescope. These observations, including a series made in conjunction with S. Shostak, reveal an extremely broad and peculiar profile, Figure 2. The full width, measured between points corresponding to 0.25 of the profile mean flux and corrected for filter broadening, is 682 ± 20 (estimated error) km s^{-1}. This is the largest value thus far found for an apparently isolated galaxy and is in good agreement with the maximum radial velocity range, 660 km s^{-1}, measured optically at the inner maxima near $\pm 25''$; see Figure 4. The even larger range in radial velocity shown by the Hα line at $\sim 60''$ to $90''$ east is contained within the full velocity extent of the H I profile.

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The midpoint velocity of the profile is 3941 km s^{-1} (heliocentric) with an estimated error of 10 km s^{-1}. Because the profile shape is so peculiar, a larger uncertainty may be present in associating this midpoint value with the systemic velocity. However, if the peculiar velocities evident in the optical data, as described below, are experienced by the neutral hydrogen, then the low optical depth likely in the H I (at these velocities) would make the H I midpoint velocity a good estimator of the systemic velocity. Here the pertinent assumption is symmetry in the peculiar velocities so that a similar distortion occurs on both sides of the velocity profile.

H I profiles obtained at the center and in the cardinal directions at positions spaced at half and full beam diameters from the center show a broadened distribution, comparable in size to the antenna beam, 10'.3 (E–W) × 11'.3 (N–S). This crude mapping also suggests an asymmetrical distribution, one extending to the north of the galaxy. These data, extrapolated to zero intensity, yield an H I mass

$$\mathfrak{M}(\text{H I})\mathfrak{M}_\odot = 2.1 \times 10^7 D_{\text{Mpc}}^{\ 2}\,,$$

with an estimated uncertainty of $\pm 15\%$. This mass is based on the usual assumption of a low H I optical depth. For the distance adopted below, 82 Mpc, the H I mass is

$$\mathfrak{M}(\text{H I}) = 1.4 \times 10^{11}\,\mathfrak{M}_\odot\,.$$

This is the highest H I mass content of a single galaxy found to date, being more representative of the *stellar* mass of a typical galaxy. Although the H I content is large, the normalizing ratios of H I mass to luminosity and H I mass to total mass are typical of galaxies of its structural type. As will be shown below, NGC 1961 is a supergiant, late-type spiral in which

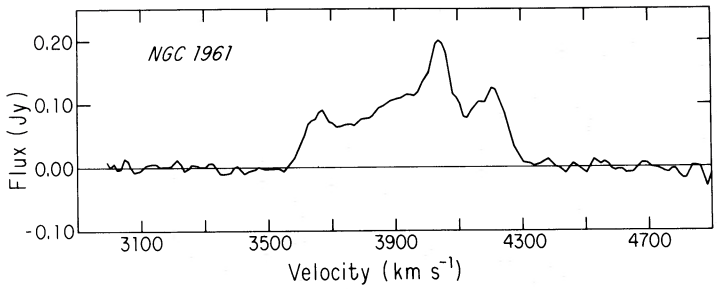

FIG. 2.—Twenty-one cm velocity profile of NGC 1961 obtained with the 300 foot telescope

its integral properties are all similarly scaled up by an order of magnitude.

b) *Optical Data*

Optical spectra of NGC 1961 with the slit aligned along the major and minor axes are shown in Figure 1. They were taken with the KPNO 4 m RC spectrograph plus Carnegie C33063 image tube, at a dispersion of 25 Å mm^{-1}. The nuclear emission is broad; beyond the nucleus the velocities of the excited gas exhibit large velocity gradients.

Measured velocities are plotted in Figure 3. A complex velocity pattern extends along the major axis from 90″ E < r < 60″ W, corresponding to 36 kpc E < r < 24 kpc W using the distance adopted below. Within the nucleus, the velocity range is about 385 km s^{-1}. Just E of the nucleus, the velocities are double valued. Along the minor axis, 40″ S < r < 45″ N, velocities exhibit real variations, but only within ±50 km s^{-1}. At larger nuclear distances along the minor axis all emission is displaced blueward.

The E side of the galaxy is approaching. Assuming that the spiral arms in the inner, more regular parts are trailing, then the S side is the near side of the galaxy. This dynamical conclusion is supported by the appearance of the dusty SW region, which is then between the observer and the galaxy.

It is difficult to know just how much symmetry we can force on NGC 1961, and even the generally straightforward task of adopting a central velocity is not simple here. The *midpoints* of the nuclear emission are (heliocentric) V_H(major) = 3882 km s^{-1}; V_H(minor) = 3912 km s^{-1}, giving $\langle V_H \rangle$ = 3897 ± 15 km s^{-1}. However, if there is a significant rotation component for the stars and gas, then the minor axis velocities will be constant at the systemic velocity, and the major axis velocities will be symmetrical about the same velocity. Surprisingly, both of these conditions are approximately satisfied, but the velocity of symmetry is not the midpoint velocity. Minor-axis velocities (P.A. 175°.1, Fig. 3*b*) are generally constant at V_H = 3970 ± 10 km s^{-1}, 40″ S < r < 45″ N ($r \sim$ 17 kpc). Major-axis velocities are symmetrical about V_H = 3958 km s^{-1} (P.A. 84°.8, Fig. 3*a*, Fig. 4) from $r \sim$ 7 kpc to the limits of the overlapping observations, $r \approx$ 20 kpc. From the agreement of these central velocities, and the forms of the major-axis and minor-axis velocity variations, we conclude that there is an underlying widespread rotation in NGC 1961, upon which are superposed velocity irregularities.

A summary of the various estimates of the systemic velocity, both radio and optical, is given in Table 1. We adopt V_H = 3940 ± 10 km s^{-1} as the central velocity for NGC 1961. With respect to the Local Group (ΔV = 300 sin l cos b), V_0 = 4106 km s^{-1}. Adopting H = 50 km s^{-1} Mpc^{-1}, the distance is 82 Mpc; 1″ = 400 pc.

The midpoint of the nuclear emission,

$$\langle V_H(\text{nuclear}) \rangle = 3897 \pm 15 \text{ km s}^{-1},$$

differs by −43 km s^{-1} from the systemic velocity. If excited gas is leaving the nucleus with a line-of-sight velocity of 43 km s^{-1}, then along the minor axis we will observe blueshifted emission from foreground gas; background (redshifted) gas could be obscured. However, motions radial from the nucleus cannot explain the asymmetrical nuclear emission along the major axis. (Radial motions will be across the line of sight along the major axis.) Hence there must be a more complex interplay of velocities arising from rotation, expansion, obscuration, and possibly nonplanar material projected near the center from the disturbed SW region.

NGC 1961 is a very large galaxy, with a diameter d = 4′.27 = 102 kpc (25 mag arcsec^{-2}, de Vaucouleurs, de Vaucouleurs, and Corwin 1976) and d = 7′.7 = 185 kpc (26.5 mag arcsec^{-2}, Holmberg 1958). Measurements of the regular inner spiral region indicate an inclination of ~50°–60°; we adopt i = 55°, but this parameter is very uncertain.

TABLE 1

SUMMARY OF SYSTEMIC VELOCITY ESTIMATES (heliocentric)

Technique	Velocity (km s^{-1})
21 cm:	
Midpoint of profile	3941 ± 10
Optical:	
Midpoint of nuclear emission	3897 ± 15
Symmetry value for major and minor axes	3965 + 10, −50
Midpoint of full range of major axis emission	3936 ± 10
Adopted:	
Heliocentric, V_H	3940 ± 10

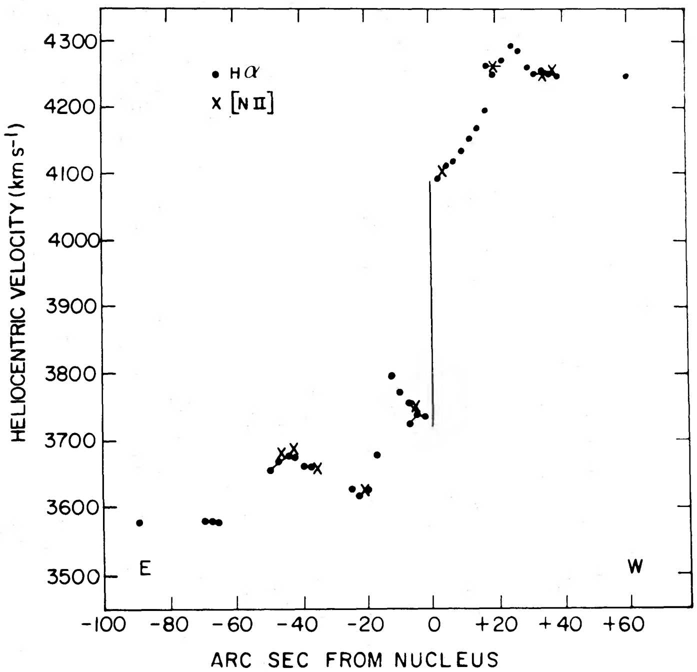

FIG. 3*a*

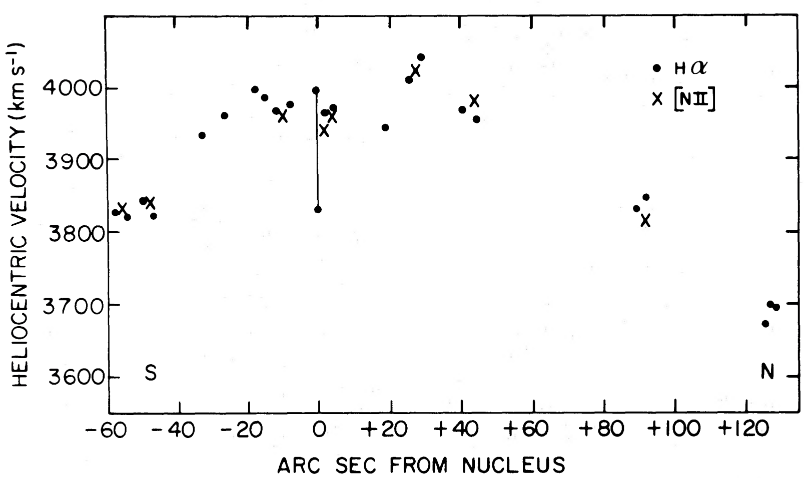

FIG. 3*b*

FIG. 3.—(*a*) Velocities along major axis of NGC 1961 (P.A. = 84°.8) as a function of distance from nucleus. Lines connect the most prominent knots. Vertical line at $r = 0$ indicates measured extent of nuclear emission. (*b*) Velocities along minor axis of NGC 1961 (P.A. = 175°.1).

Finally we note that the minor axis spectrum (P.A. = 175°.1) shows a very slight slope. From a least squares solution,

$$V = (3973 \pm 7) + (0.36 \pm 0.28)r'' ;$$

the indicated errors are mean errors. Combined with the major axis slope and position angle, these values imply a major axis of P.A. = 83°.3, rather than 84°.8 as adopted for the observations. This difference is insignificant.

III. DISCUSSION

What are we to make of this curious object? The emission line ratios appear completely normal, with [N II] λ6583 ≥ Hα in the nucleus, but Hα > [N II] in the emission knots. No unusual excitation source is indicated.

From the observed velocities and the assumption of circular motions, a very large mass is deduced. We adopt a simple spheroid model and a rotation curve flat at $V = 300\ \mathrm{km\ s^{-1}}$ (in the plane of the

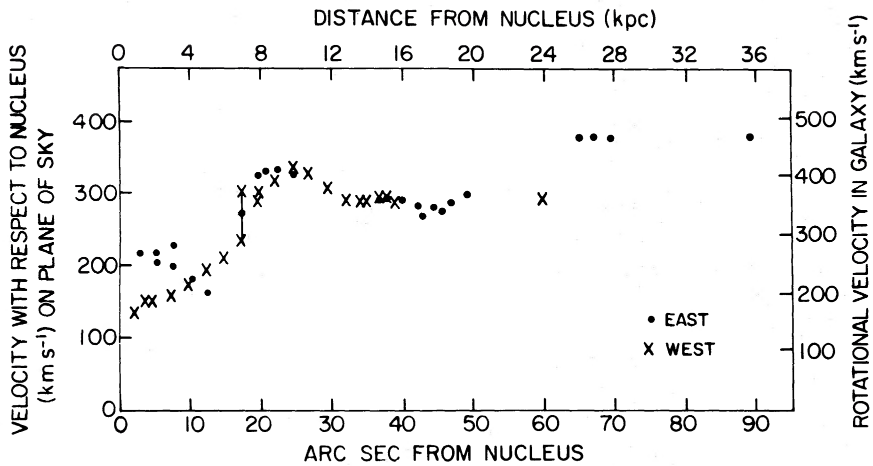

FIG. 4.—Velocities with respect to nucleus, $V = 3958 \text{ km s}^{-1}$ on plane of sky, as a function of distance along major axis. To convert to velocities in plane of NGC 1961, velocities must be multiplied by 1.22.

sky) to $r = 90''$ (36 kpc), ignoring the velocity increase $r > 65''$ (26 kpc). Then

$$\mathfrak{M}_{36\,\text{kpc}} \sim 7 \times 10^{11} (\csc i)^2\, \mathfrak{M}_\odot\,.$$

Thus even *neglecting projection effects* in the velocities (i.e., if we observe the galaxy edge-on, so the observed velocities in the plane of the sky are velocities in the plane of the galaxy—an unlikely circumstance), the mass of NGC 1961 is enormous. If $i = 55°$, then $(\csc i)^2 = 1.5$

$$\mathfrak{M}_{36\,\text{kpc}} \sim 1 \times 10^{12}\, \mathfrak{M}_\odot\,.$$

To the de Vaucouleurs radius ($r = 51$ kpc) and the Holmberg radius ($r = 92$ kpc), the mass must increase a few times this. We know of no other spiral galaxy with a mass in the range of $10^{12}\,\mathfrak{M}_\odot$, or a peak rotational velocity $V_{\text{max}} \sim 325/\sin i \approx 400 \text{ km s}^{-1}$. Galaxies are known with masses about one-third of the mass of NGC 1961: NGC 1097, 5899, 5371, 1365, and 4736 have masses which range from $1.6 \times 10^{12}\,\mathfrak{M}_\odot$ to $0.6 \times 10^{12}\,\mathfrak{M}_\odot$ (Roberts 1975, scaled to $H = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$). For comparison with other integral parameters, we adopt as the total mass within the Holmberg radius

$$\mathfrak{M}_{\text{Ho}} = 2 \times 10^{12}\, \mathfrak{M}_\odot\,.$$

As noted earlier, the completely independent determination of the interstellar H I content of NGC 1961 gives a value, $1.4 \times 10^{11}\,\mathfrak{M}_\odot$, that is comparable to the stellar mass of a typical spiral. The neutral hydrogen is generally a small component of the total mass of a galaxy. We consider this as confirmation of the remarkably large total mass of NGC 1961 derived from the rotation curve. Peculiar motions are clearly present in this system but the gross motions are consistent with the usual dynamical derivation of the total mass. The fractional content of H I, $\mathfrak{M}(\text{H I})/\mathfrak{M}_{\text{Ho}} = 0.07$, is typical of Sc type spirals (Roberts 1975). The apparent magnitude of NGC 1961, corrected to face-on and for internal and external extinction, is $B_0^T = +11.15$ mag (de Vaucouleurs, de Vaucouleurs, and Corwin 1976). A similar value, $(m_{\text{pg}})_0 = 11.02$, is derived using Holmberg's (1958) data. This latter value gives $(M_{\text{pg}})_0 = -23.55$ and $(L_{\text{pg}})_0 = 3.7 \times 10^{11} L_\odot$. Thus while the absolute magnitude is very large, the mass-to-blue luminosity ratio is small, about 5, just as found for normal spirals (Rubin, Ford, and Thonnard 1978). The distance-independent ratio $\mathfrak{M}(\text{H I})/(L_{\text{pg}})_0 = 0.38$ (solar units) is also typical for normal Sc type systems (Roberts 1975).

Morphologically, the SW dusty region in NGC 1961 resembles some of the curious structures to which the Burbidges called attention almost 20 years ago (NGC 2444–5, Burbidge and Burbidge 1959*a*; PA 665 = Arp 141, Burbidge and Burbidge 1959*b*), although in those systems the predominant galaxy is elliptical or structureless. At that time, the peculiarities were attributed either to nuclear explosions, to aftermaths of close collisions between an elliptical and a spiral, or to interactions between the galaxy and the intergalactic medium, perhaps involving magnetic lines of force. More recently, Arp (1969) has used NGC 1961 as an example of nuclear ejection to produce spiral arms.

In the climate of today's dynamical studies of galaxy evolution, it is tempting to relate NGC 1961 to a tidal interaction or a galaxy merger. Its large mass might support such a model, with the irregular SW region the remnants of a merger. However, the outward velocity of this region contradicts this view. NGC 1961 has no other nearby bright companions, although there is a small cluster of probably background galaxies at $r > 8'$ (>200 kpc projected distance at NGC 1961).

Somewhat disappointingly, the observed velocities give little evidence of the past history. The blueshifted nuclear emission indicates that gas is leaving the nucleus with V (line of sight) $\sim 43 \text{ km s}^{-1}$. Interior to $r \approx 4$ kpc, velocities along the E and W major axis are not symmetrical, but are near $V = 210 \text{ km s}^{-1}$

(E) and 150 km s^{-1} (W). Gas in the dusty SW region is also moving away from the nucleus, toward the observer; the line-of-sight velocity of approach is ~ 125 km s^{-1}, but the spatial geometry is undefined. The negative velocities N of the nucleus, ~ 300 km s^{-1} with respect to the nucleus, arise in the straight outer arms. These arms are probably not in the plane of the spiral disk, so the different geometry may account for these large velocities with respect to the nucleus.

One clue as to the past history of NGC 1961 comes from its colors [$(B - V)_T{}^0 = 0.54, (U - B)_T{}^0 = 0.13$; de Vaucouleurs, de Vaucouleurs, and Corwin 1976]. These colors place it at the lower envelope of the two-color plot of Arp Atlas (1966) galaxies, in a region containing peculiar interacting galaxies and galaxies with tidal tails, but a region unpopulated by single pathological galaxies, peculiar galaxies without tails, or morphologically normal galaxies (Larson and Tinsley 1978). Galaxy models of Larson and Tinsley indicate that colors like those of NGC 1961 can be the remnants of a burst of star formation 2×10^8 years ago, which involved 5% of the galaxy mass. This region of the two-color plane contains galaxies having the longest time interval since the star formation burst, involving the greatest fraction of galaxy mass. Hence in NGC 1961 we may be viewing the late stages of a violent dynamical event, perhaps involving a massive spiral galaxy and a companion, which initiated rapid star formation. The large mass of H I, the large total mass, the peculiar dynamical details, and the anomalous colors are all consistent with a galaxy which evolved in a region of high density and which earlier formed stars in a burst mode. In the 10^8 years since the burst, only the inner region, $r > 3$ kpc, will have completed a single revolution; the outer visible region, $r \approx 30$ kpc, will have completed only a fraction ($\sim 1/10$) of a revolution. Such a time scale seems consistent with the overall appearance of NGC 1961. NGC 1961 thus is an example of a peculiar galaxy whose dynamics and peculiar morphology may help us understand the role of dynamical events in the history of star formation and galaxy evolution.

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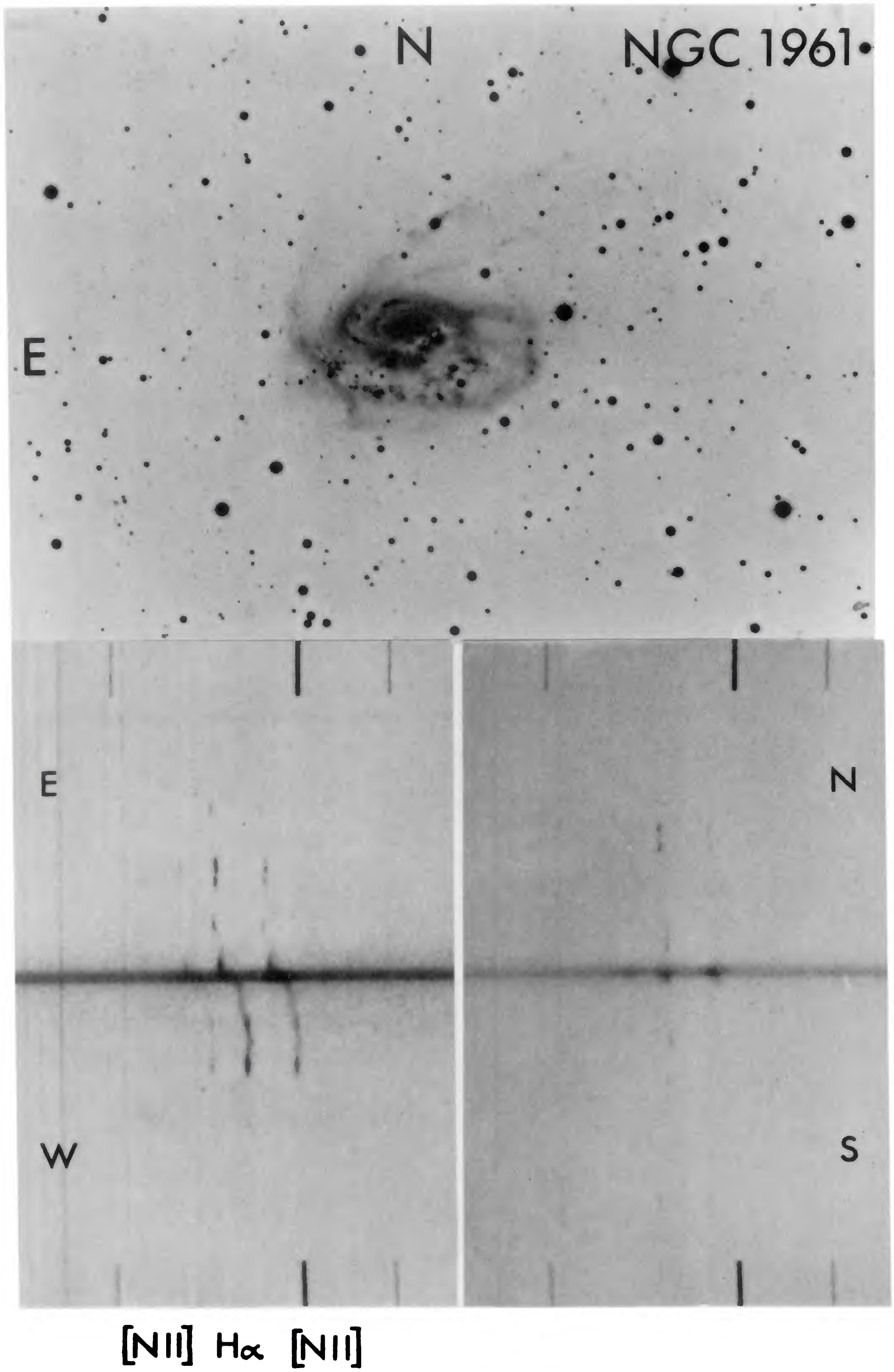

FIG. 1.—(*a*) NGC 1961, from a 200 inch plate kindly made available by Dr. H. Arp; 103a-O, 30 min exposure. (*b*) Major axis spectrum, KPNO 4 m RC spectrograph + image tube + H_2 treated + preflashed plate, P.A. = 84°.8. Original dispersion 25 Å mm^{-1}; exposure 119 min, 1977 November 16. (*c*) Minor axis spectrum, P.A. = 175°.1; plate details above; exposure 45 min, 1977 November 17.

RUBIN *et al.* (*see* page 35)