EVIDENCE FOR ACTIVITY IN THE SPIRAL GALAXY NGC4319

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ABSTRACT. Radio and optical evidence for activity in the spiral galaxy NGC4319 is presented. N4319 appears to be one of the first spirals to exhibit double lobe radio structure outside of the nuclear regions. The optical data show that 1) the quasar M205 is connected to the nucleus of N4319 and 2) that a similarly connected region on the opposite side of the nucleus is expanding towards us with V ~ 10^3 km s^{-1}. It is suggested that the unusual Hα/[NII] λ 6583 ratio (≤ 0.3) indicates that the entire central (7 kpc diameter) disk of N4319 has been shock excited by this activity.

1) Radio Activity

Radio continuum synthesis maps were obtained at 6 and 20 cm with the VLA in the B configuration. Details of the observations and reduction procedure were given in Sulentic (1986). At 20 cm, the quasar was detected as an unresolved (< 5.4 arcsec; near circular beam) source (S_{20} = 2.83 ± 0.57 mJy) with redshift implied (H_0 = 75) luminosity log L_{20} = 22.4 W Hz^{-1}. No radio emission was detected from the region of the optically luminous connection. NGC4319 was found to have a weak nuclear source (S_{20} = 0.18 ± 0.03 mJy) rather underluminous (log L_{20} = 19.1 W Hz^{-1}) for an M_B ≃ -19 spiral galaxy. The most surprising discovery was the detection of a pair of resolved 20 cm sources aligned closely (within 3 arcsec) across the nucleus of the galaxy. These candidate radio lobes have projected separations of about 7 kpc from the N4319 nucleus. Their integrated flux densities are (equal within the uncertainty) S_{20} = 1.1 ± 0.2 mJy and implied log L_{20} ≃ 20.3 W Hz^{-1}. The lobes are aligned very nearly (±5°) along the minor axis of the inner disk of N4319. Assuming an inclination i = 60° then implies a nuclear separation near 14 kpc for the lobes if they were ejected in the plane of the galaxy.

NGC4319 apparently belongs to an, at present, exclusive class of spiral galaxies exhibiting widely spaced (weak) radio lobe structure. The spiral galaxy IRAS 0421 + 040P06 also exhibits double lobe structure (separation ~ 21 kpc) (Beichman et al., 1985). A third possible case

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3C33 may be a discordant redshift galaxy (z = 0.059) if spiral structure really is being detected out to a redshift-implied radius of 37 kpc (radio lobes would be 200 kpc from the nucleus!) (Simkin and Michel, 1986). Are we seeing in N4319 the faded remains of the nuclear double lobe structure now frequently seen in Seyfert galaxies?

2) Optical Images

Direct CCD frames were obtained in U, B, R and I bands at the prime focus of the KPNO 4 meter reflector. Details of the processing are given in Sulentic and Arp (1986, submitted). Figure 1 presents a black and white reproduction of an attempt at generating a true color image of NGC4319/M205. The color image was produced by, first, decorrelating average U, B, and R frames (later coded as B, G, and R respectively) using a principal component analysis algorithm. The decorrelated images were intensity enhanced and retransformed into correlation space in order to produce the color image. Even in black and white, figure 1 reveals a wealth of structure in the inner disk of N4319 (i = 60°; PA major axis = 129 ± 3°; diameter major axis ≃ 7 kpc). N4319 exhibits two sets of spiral structure: 1) tightly wrapped barred spiral structure in the central disk and 2) diffuse outer structure (r ≃ 12 kpc ± 2) lacking the population I condensations usually associated with spiral arms. The arm nearest M205 appears completely disrupted.

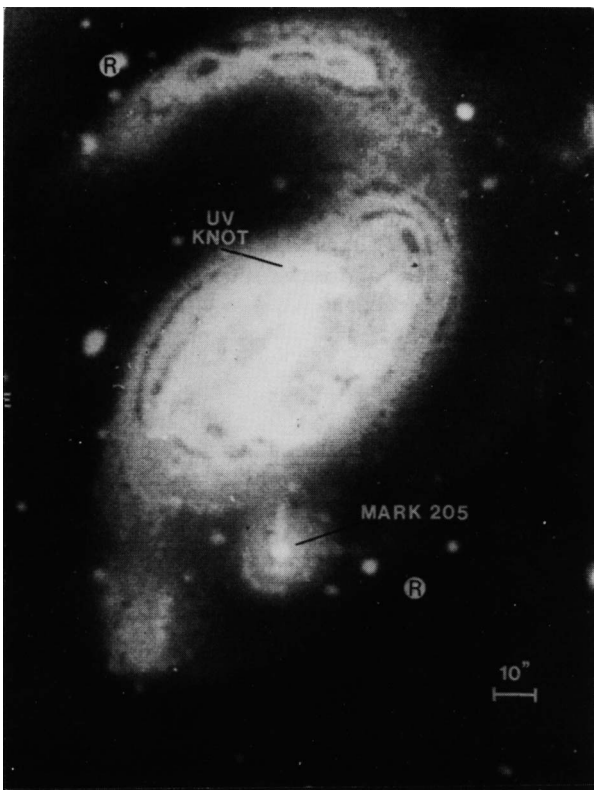

Figure 1. Black and white combination of U, B and R filter CCD images. Centers of the proposed radio lobes are indicated (R).

Are the spiral patterns in N4319 related to two successive explosive events that originated in the nucleus? The radio lobes lie just on the outer edge of the diffuse spiral structure. The sharply bounded ring-like feature formed by the inner spiral structure in N4319 resembles structure predicted in models for explosive

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events in spiral galaxies (Sanders and Bania, 1976). A rather impressive case has already been made for explosive generation of spiral structure in NGC4258 (van der Kruit et al., 1972). This concept was, of course, pioneered by Ambartsumian (1958) who related the explosive activity to the possible ejection of compact bodies from the nuclei of galaxies.

Figure 2 presents evidence that Markarian 205, and a compact UV knot diametrically opposite the N4319 nucleus, are possible ejecta of this type. There appears to be a nuclear link between the UV knot and Markarian 205. Figure 2 represents the high-pass product of a 3 arcsec horizontal median filter. A 1-D filter was used in order to suppress the confusing and more intense horizontal structure related to the inner disk spiral structure of N4319. Some artificial distortion will be produced by a 1-D filter and its effect can be monitored by examining images of stars in figure 2. It is unlikely that the filter used to produce figure 2 is simply creating a connection by enhancing the bar structure within the central disk of N4319 because 1) the position angle of the bar is 147° ± 3°, about 20-25° less than the axis of the connective feature and 2) the bar is significantly thicker (7 arcsec) than the filter dimension and will tend to be suppressed in a high pass image, and finally 3) the connective feature in fig. 2 is seen almost in its entirety on 2-D filtered images — on those images, however, it is confused by much additional structure. The original Arp (1971) connection is indicated schematically in figure 2, and the matchup with the inner filter enhanced structure is very good. The original connection is not seen in figure 2 because: 1) the charge transfer spike emerging from the N end of M205

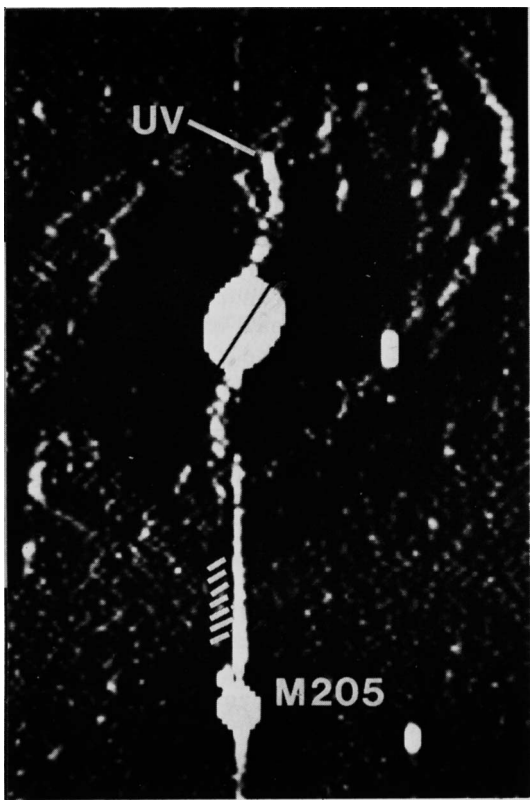

Figure 2. High pass filtered image of the N4319 inner disk and M205. Original Arp (1971) connection (white hatching) and position angle of central bar (black line; also see fig. 1) are indicated.

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lies within a kernel diameter east and parallel to it, and 2) the original connection, outside the inner disk, is broader and therefore tends to be suppressed by the filter. The inner connective structure appears to be real and confirms structure seen on both 2D median filtered photographs (Sulentic, 1983a) and 2D mean filtered CCD frames (Sulentic, 1983b; Sulentic and Arp, 1986, submitted). The matchup between the inner and outer structure directed toward M205 suggests that it, and the UV knot, are involved in a single axisymmetric luminous feature related to N4319. Do these features represent gas entrained, or star formation enhanced, along an ejection path through the disk of N4319?

3) Optical Spectra

The answer to the ejection aspect of the previous question appears to be "yes" on the basis of a careful analysis of Figure 3 which represents one of six long slit spectra obtained for N4319. Spectroscopic observations were obtained with the Cryogenic camera on the KPNO 4 meter reflector. Details of the spectroscopic observations, reductions, and analysis are given in Sulentic and Arp (1986, submitted). Figure 3 presents the Hα + [NII] region of a spectrum centered on the UV knot (18 arcsec NNW) of the nucleus. The slit was aligned E-W and a 20 pixel average (0.84 arcsec pixel^{-1}) along the slit is presented. All other spectra of the inner 7 kpc diameter disk reveal emission only in the forbidden lines [NII] λ 6548,6583. The spectra cover the wavelength

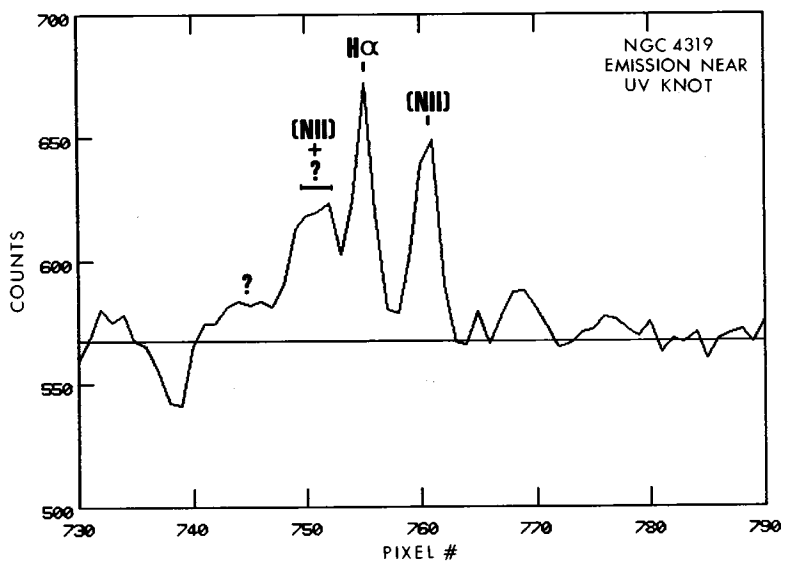

Figure 3. Region of Hα + [NII] λ 6583 in a spectrum (3.2 Å pixel^{-1}) centered on the UV knot at the N edge of inner disk of N4319. 20 pixel (0.84 arcsec pix.$^{-1}$) average along the slit on the detector. Note the excess emission blueward of Hα.

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range λλ 4200-6700 Å. The ratio of Hα/[NII] λ 6583 throughout the disk is less than 0,3. Only in an arc extending about 15 arcsec near the north edge of the inner disk was Hα detected. The strongest Hα emission is from the UV knot itself which exhibits an HII region-like ratio of Hα/[NII] = 3.1 ± 0,2. The evidence for ejection in figure 3 centers around the excess emission blueward of Hα. The width and intensity of this emission are far greater than can be ascribed to [NII] λ 6548 which should be 1/3 the intensity of [NII] λ 6583. We are observing in figure 3 either a blue wing associated with Hα or an isolated component of blueshifted [NII] λ 6583. This feature extends at least 15 Å blueward of Hα. Velocity field measurements from the present slit spectra place the UV knot on the near side of N4319. Since most of this feature is located within 45° of the minor axis of the galaxy, it is most likely to represent radial expansion assuming the gas is located in the disk of N4319. If the gas is attributed to Hα, the deprojected ejection velocity (at r_o = 3 kpc) is V ~ 900 km s^{-1} while a much larger value of V ~ 2100 km s^{-1} results if the feature represents [NII] λ 6583. The UV knot itself also shows a blue shift (of V ~ 70 km s^{-1}) relative to the stars and more extended [NII] λ 6583. Ejection can therefore be unambiguously ascribed to the region of the UV knot which is connected to the N4319 nucleus by the same axisymmetric structure that appears to link Markarian 205. The expanding gas and UV knot are probably coincident with a resolved radio source noted by Willis (1979) as displaced north of the N4319 nucleus.

4) A Shocked Disk?

A final comment is appropriate on how the unusual emission line spectrum of N4319 might relate to the proposed activity. Low values for the Hα/[NII] λ 6583 ratio in spiral galaxies were first discussed in detail by Burbidge and Burbidge (1962). They found typical values in the spiral arm regions of ~3, presumably arising from photoionization by OB stars. In some spirals, the value was observed to decrease somewhat in the central regions, often becoming << 1 in galactic nuclei particularly of earlier type (now called LINERS). A consistantly low (≤0.3) ratio throughout an entire 7 kpc. diameter disk structure replete with spiral arms is then almost unprecedented. Our coverage of the inner disk is not complete, but it is sufficient for us to describe the general properties of the extended gas component.

It is possible that an initial event related perhaps to the formation of the outer spiral arms, or to the expanding arc, swept most of the original gas out of the N4319 disk. The weak [NII] emission that we are now observing in the disk might then come from the nitrogen abundant mass loss of evolving stars. It does not seem reasonable to assign the unusual Hα/[NII] ratio entirely to such an overabundance of nitrogen from evolved stars, as has been suggested for M81 (Goad, 1976).

The alternate viewpoint is to consider the unusually strong [NII] (relative to Hα or [OIII]; [OII] not observed) as indicative of unusual excitation conditions in the disk. Burbidge et al., (1963) considered various mechanisms and concluded that a high electron temperature (T_e ≥ 2 x 10^4 K) was the most reasonable possibility. One mechanism for

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producing such a high T_e would involve shock excitation of the disk due to a violent release of energy in a galactic nucleus. Recently, the ionization mechanism of choice has become photoionization by a nonstellar continuum. We favor the former interpretation for NGC4319 because, as the previous sections of this paper have independently shown, explosive events have occurred there. Explosive events are almost certain in other galaxies with LINER spectra as well (Eg. NGC4736, van der Kruit (1974) and NGC5194, Ford et al., (1985)). Comparison with other sources and models with unusual Hα/[NII] ratios suggest that [OII] λ 3727 would be equal to or greater in strength than [NII] λ 6583. This may explain why the late (K) population disk of N4319 was so well recorded on relatively short exposure U images (I_U = 0.5(±0.1) I_B pixel^{-1}).

The expanding arc near the UV knot suggests that the (most recent?) explosive event would have originated in the nucleus about 3 x 10^6 years ago. Subsequent to this event, the gas in the disk would undergo rapid cooling. Burbidge et al., (1963) consider different methods for injecting additional energy into the gas in order to maintain the high values for T_e, and hence the observed spectrum. It would be interesting to consider further the effects of an adjacent power law source like M205 ($M_B \simeq -17$) and its large flux of UV photons within this context (see Adams and Weymann, 1972). A search for temperature sensitive lines like [OII] λ 4363 could prove extremely useful (if $N \leq 10^5$ cm^{-3}) for defining the physical conditions within the N4319 disk.

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