THE ASTROPHYSICAL JOURNAL, **268**:102–104, 1983 May 1

SPATIALLY EXTENDED NARROW EMISSION-LINE GAS IN THE SEYFERT GALAXY NGC 4151

TIMOTHY M. HECKMAN[1]
Astronomy Program, University of Maryland

AND

BRUCE BALICK[1]
Department of Astronomy, University of Washington
Received 1982 August 23; accepted 1982 October 27

ABSTRACT

We present narrow-band images of the emission-line gas in the type 1 Seyfert galaxy NGC 4151. These data are compared with optical spectroscopic data, radio continuum maps, and (especially) with new X-ray imaging data (Elvis, Briel, and Henry). Both the emission-line gas and X-ray gas are asymmetrically extended to the SW of the nucleus. The quiescent kinematics of the emission-line clouds would seem to preclude models in which the clouds themselves are accelerated out of the nucleus, subsequently collide with the ambient medium, and so produce X-rays. Instead, we argue that the extended emission-line region is ambient interstellar material which is photoionized by X-rays emitted from an adjacent region of shocked interstellar gas. The narrow, elongated morphology of the extended emission-line region would then suggest that the nucleus supplies energy to its environs in a collimated fashion. This collimated supply of energy may be directly related to the radio jets observed in the vicinity of the emission-line and X-ray gas.

Subject headings: galaxies: individual — galaxies: nuclei — galaxies: Seyfert — galaxies: structure — radiation mechanisms

I. INTRODUCTION

Recent high resolution studies of the extranuclear regions of active galaxies have been successful in showing that optical emission-line gas and nonthermal radio plasma are often found proximate to active galactic nuclei (AGNs) (e.g., Ulvestad, Wilson, and Sramek 1981; Weedman 1977; Heckman *et al.* 1981; Balick and Heckman, in preparation). In a companion paper Elvis, Briel, and Henry (1982, hereafter EBH) report the discovery of extended X-ray emission whose size scale is comparable to that of extended radio emission in the type 1 Seyfert galaxy NGC 4151 (Johnston *et al.* 1982; Booler, Pedlar, and Davies 1982; Wilson and Ulvestad 1982).

EBH suggest that the extended X-ray emission is intimately associated with the extranuclear region in which relatively narrow emission lines arise—the narrow line region, or NLR. In this paper we present details of the spatial structure of the NLR in NGC 4151, and we compare the structure of the NLR to that of the radio and X-ray emission. Together with the results of long-slit spectroscopy of the NLR (Heckman *et al.* 1981), these data place interesting constraints on the nature of the energy transfer between the nucleus and the various extended emission regions nearby.

[1] Visiting Astronomer at the Kitt Peak National Observatory, operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

II. OBSERVATIONS

Images of NGC 4151 over a 70″ region were obtained through various narrow- and wide-band filters using the video camera on the 4 m telescope at the Kitt Peak National Observatory. The data acquisition, calibration, and processing techniques are described elsewhere (Heckman and Balick 1979; Balick and Heckman 1981). The seeing was 1″.0 ± 0″.2, the transparency was photometric, and the dynamic range of the data is ~500. The final images consist of continuum-subtracted images in the light of [O II]λ5007 and Hα + [N II]λ6584 emission lines, line-free continuum images at about the same wavelengths, and a deep *V*-band image. The emission line images are shown in Figures 1 and 2 (Plate 1). The extent and relative strength of the extended emission in P.A. 45° in the figures is in good agreement with the spectroscopic data reported in Heckman *et al.* (1981). Thus, there is little concern that the extranuclear emission regions seen in these figures are ghost images.

III. RESULTS

a) *Morphology of the NLR*

Within 30″ of the nucleus are find:

1. A bright elliptically shaped "crown" centered on the nucleus. The crown has dimensions 5″ × 3″, or $0.25h^{-1} \times 0.15h^{-1}$ kpc, where $h = H_0/100$ km s^{-1} Mpc^{-1}, in position angle P.A. = 55 ± 10°. (Hereafter we assume $h = 0.5$.)

2. A narrow, knotty feature extending 1.8 kpc in P.A. $228 \pm 5°$. The brightest knots lie nearly colinearly within a 10° cone as seen from the nucleus at projected distances of about 8, 11, 16, and 18″. The knots seem to be slightly resolved with characteristic dimensions of ~0.2 kpc.

3. A knot or protrusion located ~5″ (0.5 kpc) NE of the nucleus in P.A. $75 \pm 10°$.

4. A diffuse halo of emission lying mostly E and N of the nucleus and extending at least 10″ from the nucleus.

5. A knot located ~16″ N of the nucleus.

In comparison, the extended X-ray emission region is centered ~5″ from the nucleus in P.A. ≈ 225°. The extranuclear radio emission is extended ~10″ in P.A. ≈ 77° and is strongest to the NE. Hence, the X-ray source lies between the nucleus and the knotty feature 2 above, whereas the most likely counterparts of the radio emission are features 3 and 4.

b) *Excitation of the NLR*

From a crude calibration of the present images and from the long-slit data of Heckman *et al.* (1981) it is clear that most of the NLR is much brighter in the light of [O III] than in Hα + [N II]. Heckman *et al.* (1981) find that [O III]λ5007/Hβ ≈ 10 along P.A. ≈ 45°. The spectrum of the narrow-line gas in the direction of the nucleus (Osterbrock and Koski 1976) gives about the same results, viz., [O III]/(Hα + [N II]) ≈ 3.7 for the narrow lines. Hence, with one exception, the entire NLR seems to have a uniformly high state of ionization and is probably ionized by the nucleus either directly or indirectly.

The exception is the northern knot (feature 5) which is not seen in the [O II] image. It is plausible that this knot is an ordinary H II region, based on available data.

c) *Luminosity of the Extranuclear Features*

From the [O III] images and spectroscopic data (Heckman *et al.* 1981; Lawrence and Elvis 1982) we find:

1. Most (~90%) of the [O III] flux comes from the crown. Much of the remainder comes from the knots to the SW of the nucleus.

2. We estimate a total emission line luminosity in the SW knots to be 10^{41} ergs s^{-1}, much the same as the luminosity of the extranuclear X-rays observed in the same region (EBH).

3. The mass of ionized gas is given approximately by $M_g \approx (L_g/10^{36} \text{ ergs s}^{-1})(N_e/100 \text{ cm}^{-3})^{-1} M_\odot$, where L_g is the emission line luminosity and N_e is the electron density of the emitting gas.

d) *Kinematics*

To summarize the salient results of Ulrich (1973), Fricke and Reinhardt (1974), and Heckman *et al.* (1981):

1. Within 2″ of the nucleus lie several distinct kinematic components ("cells") near P.A. ≈ 55°, most having blueshifted velocities relative to the galaxy's systematic velocity (by ~200–500 km s^{-1}). Such blueshifts are common features in active galaxies according to Heckman *et al.* (1981), who argue that dust plus radial (outbound?) flows from the nucleus are responsible.

2. Beyond 4″ from the nucleus in P.A. 45° and 225° the emission lines are unresolved (width < 100 km s^{-1}) and the pattern of motions is consistent with the normal galactic rotation of NGC 4151 (Bosma, Ekers, and Lequeux 1977).

3. Fricke and Reinhardt report peculiar (noncircular) motions at radii larger than 20″ from the nucleus with characteristic velocities of ~$10^{2.5}$ km s^{-1}. Heckman *et al.* (1981) were unable to confirm these results, and the present video camera images show no signs of line emission at these radii.

IV. DISCUSSION

EBH consider several possibilities for the origin of the X-ray emission detected ~5″ SW of the nucleus. These and other models are now tested with the results above.

1. *The X-ray gas is in pressure equilibrium with the adjacent NLR.*—This model is suggested by the spatial proximity of the extended X-ray and line-emitting regions. It is possible to derive an estimate for the pressure in the NLR near the region of extended X-ray emission. The ultraviolet luminosity of the nucleus of NGC 4151 determined by Perola *et al.* (1982) implies a value for the ionizing photon density 0.5 kpc from the nucleus. The photoionization models of Ulrich and Pequignot (1980) in turn require that the ratio of the gas density–to–ionizing photon density (the "ionization parameter") falls within a narrow range to explain the ionization character of the emission-line spectrum. Thus, under the assumption that the gas 0.5 kpc from the nucleus is photoionized by the nucleus, we can derive a value for the local gas density of ~$10^{2.5}$ cm^{-3}. Assuming standard values of the electron temperature, the pressure in the NLR at 0.5 kpc is ~$10^{6.5}$ cm^{-3} K. Following EBH, the expected X-ray luminosity of hot regions at the same pressure would be 10^{40} (10^{41}) ergs s^{-1} if the temperature is 10^7 (10^6) K, close to the observed value of L_x.

2. *The X-ray gas is shock-heated NLR clouds flowing supersonically through the ambient galactic interstellar medium* (*ISM*).—As above, this model is motivated by the spatial similarities of the X-ray and emission line gas. However, kinematic data obtained ~5″ SW of the nucleus fail to show evidence of supersonic motions in the NLR relative to the overall pattern of the galaxy.

There is a possibility that cloud II (Ulrich 1973) and the X-ray gas may be related. Heckman *et al.* (1981) find that although cloud II is centered 1″.5 SW of the nucleus, it may extend as far as 5″ in P.A. 225°. The cloud has a blueshift of 275 km s^{-1} from the systematic velocity of NGC 4151. If this motion arises because the cloud moves radially from the nucleus, then X-ray emission might arise at the leading front of the cloud. Further data are needed to explore this possibility.

3. *The X-rays arise in SNR and massive X-ray binaries produced in bursts of star formation stimulated by nuclear outflow.*—The character of line emission is not that of H II regions, and few data which might support the

model of a prodigious star formation rate (other than the X-ray results) are available.

4. *The X-ray and line emission regions are ionized indirectly by the radio jet.*—EBH noted that the P.A. of the X-ray emission regions differs from the P.A. of the radio jet by 32°. The present data show similar disparities between optical and radio features. However, at a projected distance of 5″, the separation between the radio jet and the various optical and X-ray features is only ~0.3 kpc, which is not atypical of the situation in several radio-loud active galaxies with associated emission-line and radio continuum regions (van Breugel and Heckman 1982).

van Breugel and Heckman (1982) have proposed that material in a jet can be deflected by collision with dense interstellar clouds. X-rays can be produced at the interface of the clouds and the jet. These X-rays can ionize portions of the ambient ISM and give rise to optical emission-lines. In this case the kinematics of the X-ray photoionized quiescent gas need not be strongly affected by the jet or the X-ray emission. The observed kinematics, line intensity ratios, and the spatial structures SW of the nucleus are all in accord with the model. It is then curious, but not catastrophic, that the strongest radio emission lies to the NE of the nucleus, while the strongest X-rays lie to the SW. Perhaps the jet may simply be more efficient at producing radio emission to the NE. Potentially a more serious problem is that the optical emission extends much further from the nucleus in every direction than does the radio and X-ray emission. However, this may be an observational effect owing to sensitivity and dynamic range limitations in the radio and X-ray data relative to the optical data.

We differ slightly from EBH in the interpretation of the data available for NGC 4151. No matter which model is ultimately best justified, it is clear that the combination of spatially resolvable regions of X-ray, optical-line, and radio continuum emission in and near the nucleus of NGC 4151 makes this a uniquely valuable object in the attempt to understand the relationship between an AGN and its immediate environment.

We wish to thank Harvey Butcher and the staff of the KPNO for their help with the acquisition and reduction of the video camera data. We acknowledge the support of NASA grant NAG 8405. T.M.H. thanks the General Research Board of the University of Maryland for support while this paper was written.

REFERENCES

Balick, B., and Heckman, T. M. 1981, *Astr. Ap.*, **96**, 271.
Booler, R. V., Pedlar, A., and Davies, R. D. 1982, *M.N.R.A.S.*, **199**, 229.
Bosma, A., Ekers, R. D., and Lequeux, J. 1977, *Astr. Ap.*, **57**, 97.
Elvis, M., Briel, U. G., and Henry, J. P. 1982, preprint (EBH).
Fricke, K. J., and Reinhardt, M. 1974, *Astr. Ap.*, **37**, 349.
Heckman, T. M., and Balick, B. 1979, *Astr. Ap.*, **76**, L7.
Heckman, T. M., Miley, G. K., Butcher, H. R., and van Breugel, W. J. M. 1981, *Ap. J.*, **247**, 403.
Johnston, K. J., Elvis, M., Kjer, D., and Shen, B. S. P. 1982, *Ap. J.*, in press.
Lawrence, A., and Elvis, M. 1982 *Ap. J.*, **256**, 410.
Osterbrock, D. E., and Koski, A. T. 1976, *M.N.R.A.S.*, **176**, 61P.
Perola, G. C., *et al.* 1982, *M.N.R.A.S.*, **200**, 293.
Ulrich, M. H. 1973, *Ap. J.*, **181**, 51.
Ulrich, M. H., and Pequignot, D. 1980, *Ap. J.*, **238**, 45.
Ulvestad, J. S., Wilson, A. S., and Sramek, R. 1981, *Ap. J.*, **247**, 419.
van Breugel, W. J. M., and Heckman, T. M. 1982, in *IAU Symposium 97, Extragalactic Radio Sources*, ed. D. S. Heeschen and C. M. Wade (Dordrecht: Reidel), p. 61.
Weedman, D. W. 1977, *Ann. Rev. Astr. Ap.*, **15**, 69.
Wilson, A. S., and Ulvestad, J. S. 1982, preprint.

BRUCE BALICK: Department of Astronomy, University of Washington, Seattle, WA 98195

TIMOTHY HECKMAN: Astronomy Program, University of Maryland, College Park, MD 207742

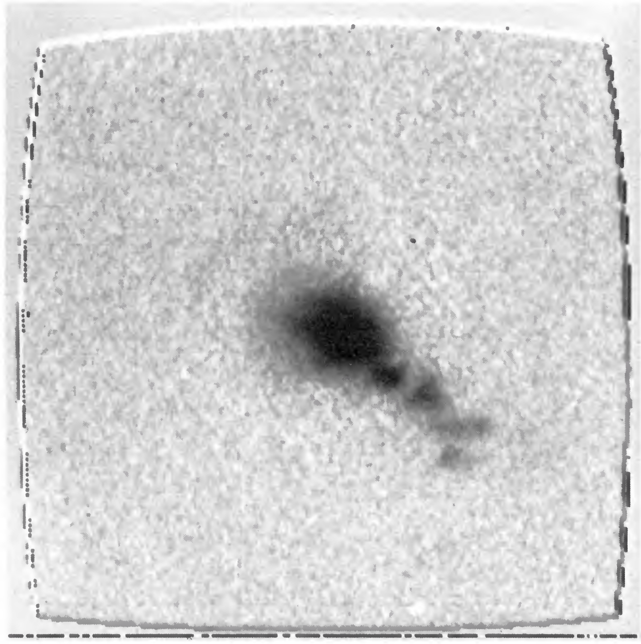

FIG. 1

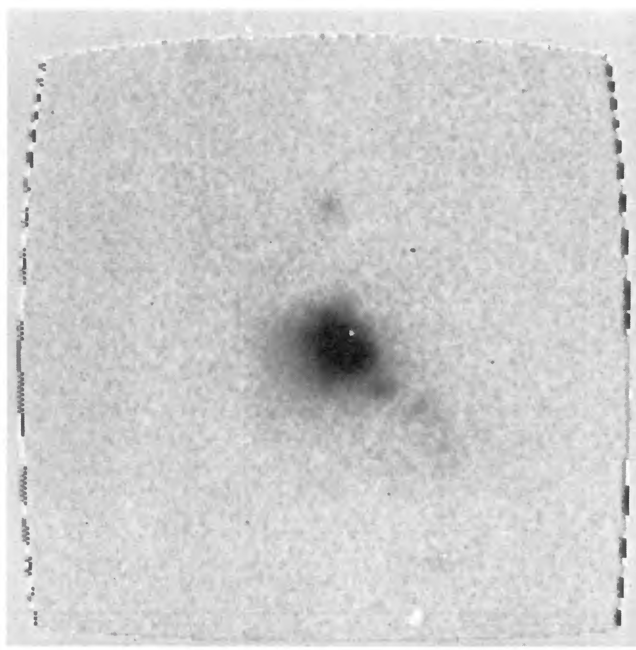

FIG. 2

FIG. 1.—Gray-scale representation of the continuum-free image of the NLR in NGC 4151 in the light of [O III] λ5007. The field is $\sim$70″ square, with north to the top and east to the left. The displayed image was constructed using a logarithmic transfer function to connect image intensity to gray-scale value. The total dynamic range of the image is $\sim$500:1.

FIG. 2.—Same as Fig. 1, except that the NLR is displayed in the light of Hα + [N II] λ6584.

HECKMAN AND BALICK (*see* page 102)