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[O III] EMISSION SURROUNDING THE QUASAR MR 2251 − 178

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ABSTRACT

Narrow-band images in [O III] λλ4959, 5007 and Hβ of the field of the low-redshift quasar MR 2251 − 178 have revealed, in addition to nebulosity closely associated with the quasar, diffuse [O III]-emitting regions separated by up to 100 kpc from the nucleus but kinematically associated with it. These regions of enhanced [O III] emission are attributed to density perturbations of the gaseous envelope, or disk, which rotates about the quasar. A tidal interaction between MR 2251 − 178 and a nearby active galaxy in the same cluster, which we infer to have occurred between 2 and 4 × 10^8 yr ago, is identified as a plausible cause of these density perturbations.

Subject heading: quasars

I. INTRODUCTION

The nearby quasar MR 2251 − 178, discovered by Ricker *et al.* (1978) on the basis of its X-ray emission, is known to possess significant nebulosity surrounding the stellar core (Ricker *et al.* 1979; Phillips 1980) and to lie within a small cluster of galaxies (Phillips 1980; Bergeron *et al.* 1983). Long-slit spectroscopic observations of the quasar, the associated nebulosity, and some of the nearby galaxies by Bergeron *et al.* resulted in the discovery of a giant envelope of ionized material surrounding and kinematically associated with the quasar, revealed by the presence of weak [O III] λ5007 emission up to 170 kpc or more from it ($H_0 = 50$ km s^{-1} Mpc^{-1}).

Incomplete mapping of the extent and kinematics of the ionized region did not permit Bergeron *et al.* to attribute the origin of the ionized gas either to the interstellar matter of an underlying galaxy or to accreted material, although the weak compact radio structure (Ricker *et al.* 1978), the high degree of ionization deduced from the ratio [O III] λλ4959, 5007/Hβ in the outer nebulosity, and the mass of ionized gas inferred for the nebulosity led Bergeron *et al.* to propose that the emissive region could be the interstellar matter of a spiral galaxy, ionized by hard radiation from the active nucleus.

The evident importance of the [O III] λ5007 line emission as an indicator of the environment of the active quasar nucleus, the uncertain nature of the underlying nebulosity and giant envelope surrounding the object, and the proximity of MR 2251 − 178 to the transition between Seyfert 1 and quasar properties (we will nevertheless follow the discoverers and refer to the object as a quasar) led us to undertake narrow-band imaging of the field using interference filters centered on redshifted Hβ, [O III] λλ4959, 5007 and continuum, to define more completely the morphology and nature of the emission-line region, and to complement and aid interpretation of the long-slit spectroscopic observations.

II. OBSERVATIONS AND REDUCTIONS

Direct images of the field of MR 2251 − 178 were obtained on the night of 1983 July 13 using the ESA Photon Counting Detector (PCD) at the Cassegrain focus of the ESO 3.6 m telescope at La Silla. The detector, developed as a prototype for the Faint Object Camera for the Space Telescope, is described in detail by di Serego Alighieri, Perryman, and Macchetto (1984).

A series of three exposures was made using interference filters centered at 5009 Å (continuum), 5200 Å (redshifted Hβ), and 5305 Å (redshifted [O III]) of FWHM 103 Å, 91 Å, and 96 Å, respectively. Exposure times were 1700, 1600, and 1800 s, respectively. The two on-line interference filters were chosen to include Hβ and [O III] λλ4959, 5007, respectively, covering emission both at the redshift of the quasar, $z = 0.06398$, and at the average redshift of the surrounding cluster, $z = 0.0668$ (Bergeron *et al.* 1983). An image format of 512 × 512 50 μm pixels was used, giving a scale of 0.38 arcsec per pixel and a resulting field of view of 3.2 × 3.2 $arcmin^2$.

Differential images were constructed from the digital data to derive [O III] − continuum and Hβ − continuum images. Seeing conditions were variable, with the stellar profiles being well represented by Gaussians with FWHM of 1″.6 (continuum), 2″.9 (Hβ), and 2″.1 ([O III]). The corresponding stellar positions were used to register the Hβ and [O III] images with the continuum image, with residual displacements not amounting to more than about 1 pixel throughout the field. Large-scale image distortions have not been corrected. Individual images were scaled to give the same average background as that found for the continuum exposure, the scaling factors employed corresponding to within 5% of the values predicted from the integration times, filter bandwidths, and filter efficiencies, and providing excellent subtraction of the galaxies and fainter stars in the field. The differential images were then smoothed with a Gaussian of FWHM = 4 pixels over an area of 7 × 7 pixels. The resulting images are shown in Figures 1 and 2 (Plates 10 and 11), respectively, using the same transfer function with white at 0 counts and black at 60 counts. Background counts for all raw images were around 300 counts,

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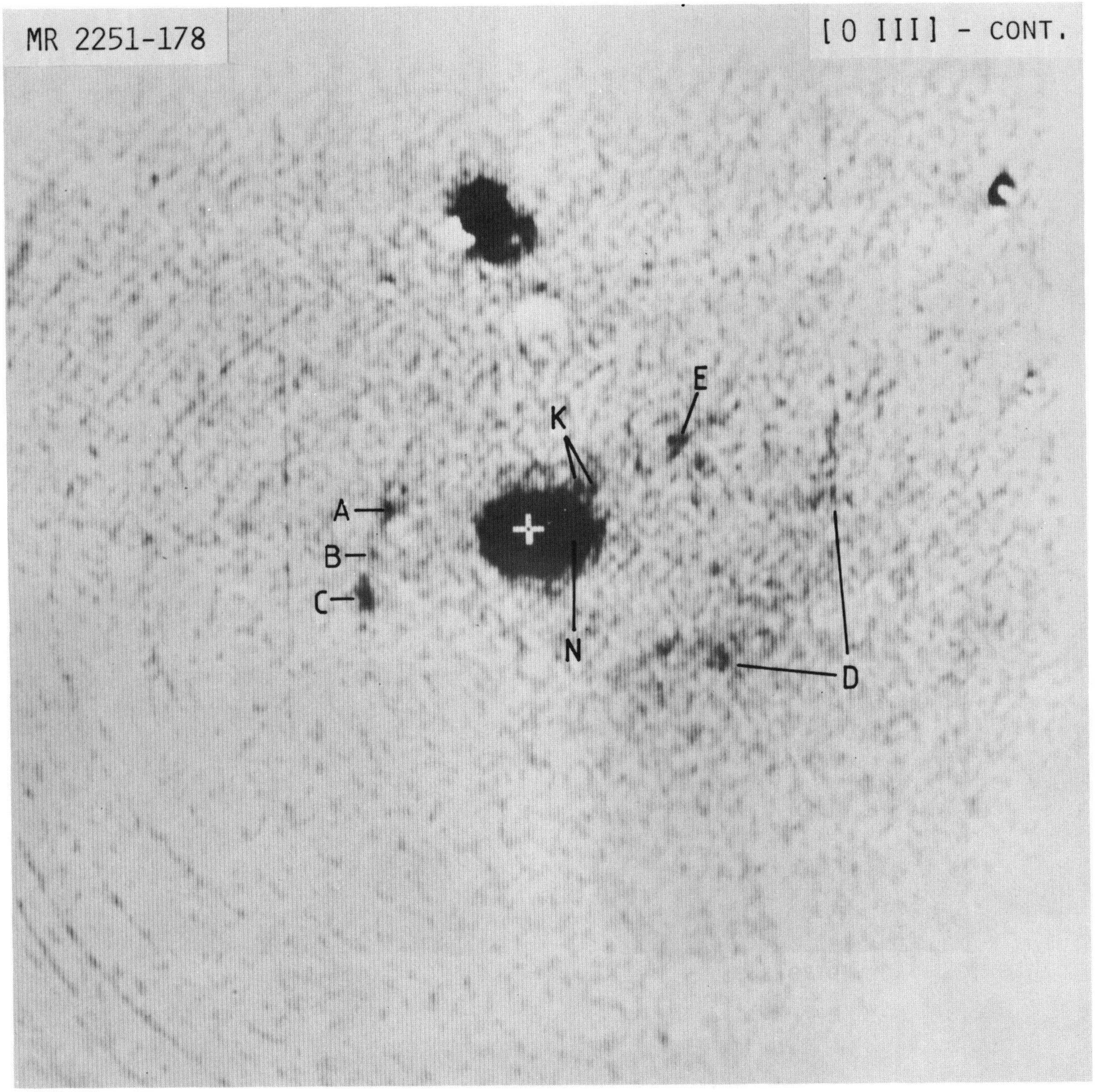

FIG. 1.—The field of MR 2251 − 178 seen as the difference between exposures in redshifted [O III] λλ4959, 5007 and scaled line-free continuum. The field is 3.2 × 3.2 arcmin^2, with north to the top and east to the left.

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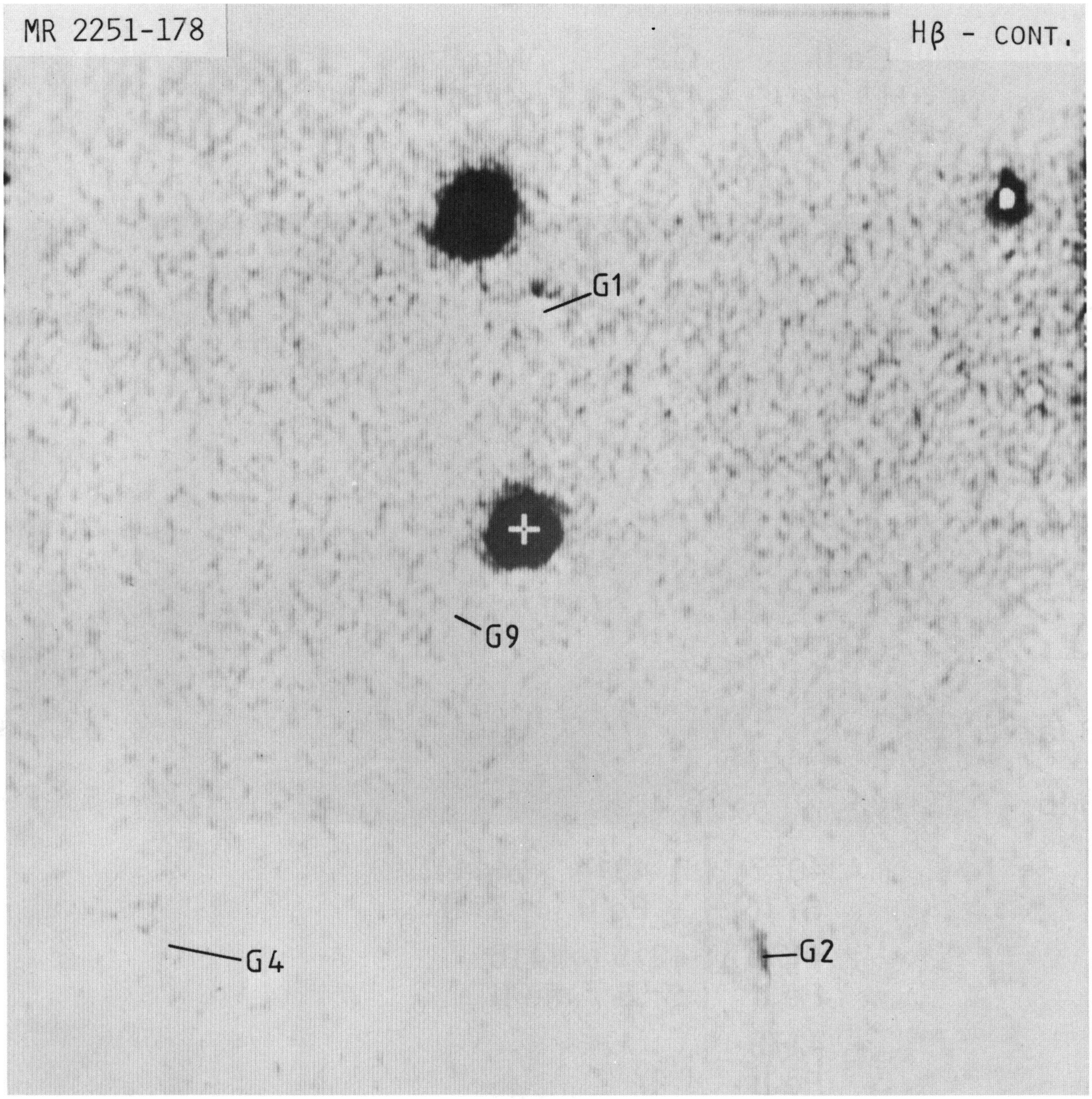

FIG. 2.—As Fig. 1, but seen as the difference between exposures in redshifted Hβ and the scaled line-free continuum. The positions of galaxies, according to the notation of Phillips (1980) and Bergeron *et al.* (1983), are marked.

DI SEREGO ALIGHIERI, PERRYMAN, AND MACCHETTO (*see* page 567) and the photon noise on the smoothed differential images is about 7 counts per pixel (1 σ).

Although the majority of the stars used for the registration of the individual images have subtracted almost completely, some residual positive or negative regions displaced by about 1 pixel can be seen, especially around galaxy G2. These features have arisen because of the different seeing profiles for the different images, which should not, however, have a significant effect on the extended emission features in which we are particularly interested. Poor suppression of the brightest objects is a result of the nonlinear intensity transfer function of the PCD at high exposure levels. The small equivalent width of the Hβ line and the continuum shape of galaxy G1 (Bergeron *et al.* 1983) explain the absence of galaxy G1 in the Hβ – continuum image.

Two detector imperfections are visible in the final images. The first of these are vertical lines at scan lines 128 and 384 resulting from digital-to-analog glitches in the camera electronics unit (as displayed, the scans were made from top to bottom, right to left). The second is the series of concentric, roughly parabolic rings, especially visible at the left edge of Figure 1, which are a result of the interference of the read-out electron beam with the field mesh and target array structure in the TV camera.

III. RESULTS

The background of the Hβ – continuum image (Fig. 2) is rather flat, showing little evidence for non-instrumental large- or small-scale structure. The most striking features of the [O III] – continuum image (Fig. 1) are, by contrast, the nebulosity associated with the nucleus noted by previous workers (the center of the nucleus is marked by a cross in both images) and the presence of regions of significant emission farther from the nucleus.

From a comparison of Figures 1 and 2 the nebulosity associated with the nucleus (area N in Fig. 1) can be seen to originate mostly from the [O III] emission, being observed as a predominantly westward, elliptical extension up to approximately 13″ (22 kpc) from the central peak. Additional condensations or knots (the two most prominent are labeled K in Fig. 1) and possible filamentary structures are seen to the northwest of this nebulosity.

Emission farther from the nucleus includes three prominent regions (A–C) about 25″ (40 kpc) to the east of the quasar nucleus, together forming an "arm" some 18″ (30 kpc) in extent, a more diffuse region (D) extending from 40″ (70 kpc) southwest of the nucleus to some 60″ (100 kpc) to the west of it, and another prominent region (E) some 30″ (50 kpc) to the northwest of the nucleus. There is marginal evidence for emission in areas A and C in the blue photograph (Pl. 2) of Bergeron *et al.* (1983). Our mapping of the [O III] emission is consistent with the corresponding detections indicated by a thick continuous line on the slit positions covered by Bergeron *et al.* in their Plate 2, and the overall morphology of the [O III]-emitting structure is provisionally confirmed by additional long-slit spectroscopic observations recently obtained by Bergeron (1983).

Measurements of the [O III] $\lambda\lambda$4959, 5007 and Hβ flux ratios permit a coarse assessment of the ionization conditions in the vicinity of the quasar to be made. Estimates of the [O III]/Hβ ratio for some of the regions shown in Figure 1 are given in Table 1. Error estimates include the effects of photon noise and uncertainty in the background level in both differential images. Lower limits of typically [O III]/Hβ > 10 over much of region D result from the general absence of detected Hβ emission at large distances (> 20 kpc) from the quasar, consistent with the claims of Bergeron *et al.* We do, however, detect very weak Hβ emission in a few localized regions, especially in areas A and E. In these areas we derive somewhat lower values of [O III]/Hβ of about 4, while in region C and in the nebulosity to the W of the nucleus [O III]/Hβ > 10. We nevertheless consider that more sensitive observations are required to confirm the weak Hβ detections, and hence place more reliable limits on the derived [O III]/Hβ ratios.

TABLE 1

PARAMETERS FOR THE EXTENDED EMISSION-LINE REGIONS

Region	[O III]/Hβ[a]	Area (kpc^2)	[O III] Luminosity[a] (10^{40} ergs s^{-1})
A	4 ± 1	7×3	9
B	6 ± 4	$<3 \times 3$	5
C	>10	9×4	11
E	5 ± 2	7×6	10
K[b]	4 ± 2	$<4 \times 3$	4

[a] [O III] intensities and luminosities refer to $\lambda\lambda$4959, 5007.

[b] Mean for the two knots indicated in Fig. 1.

IV. DISCUSSION

We first consider the possibility that the extended [O III] emission delineates two arms of a very large spiral galaxy in which the quasar nucleus resides. This possibility is suggested by the emission-line morphology, and by the form of the rotation curve, which shows a central velocity gradient of 17 km s^{-1} kpc^{-1} out to 6 kpc and a small dip near 10 kpc, rising to a broad maximum of about 180 km s^{-1} at about 120 kpc to the SE, and reaching a value of about -60 km s^{-1} at greater than 25 kpc to the NW. Elongation of the emitting structure in the E–W direction seen in Figure 1 is consistent with the range of position angles (270°–319°) given by Bergeron *et al.* for the major axis of the rotating nebulosity. We have derived estimates of the inclination angle based upon subjective measurements of the axial ratio of the extended emitting region assuming circular outer structure. A value of $i = 40° \pm 10°$ appears to be plausible, although, because of our assumptions, lower values cannot be excluded. Assuming that the inclination angle $i = 30°–50°$, the corrected rotational velocities lie in the range $v_{\rm corr} = 1.3–2v_{\rm obs}$, and the rotation curve corrected for in this way then bears a quantitative similarity to the rotation curves for spiral galaxies, especially to those of types Sb and Sc (Rubin, Ford, and Thonnard 1980; Rubin *et al.* 1982). The maximum diameter of the emitting structure would be some 140 kpc from region C to the westernmost extension of region D—very large compared with the optical diameters of normal spiral galaxies, although comparable to the scales of extended H I envelopes known to exist around some nearby spiral galaxies (e.g., Huchtmeier and Richter 1982). Other quasars have been inferred to lie within even larger gaseous halos or disks (e.g., Shaver and Robertson 1983), although the detailed morphologies and kinematics of these envelopes have not, so far, been determined.

Sizes, luminosities, and [O III]/Hβ ratios for the regions of enhanced line emission are given in Table 1. Our luminosity calibration is based on a comparison of our counts within the nebulosity with the [O III] flux for the same region given in Table 2 of Bergeron *et al.* (1983), and as a result the tabulated luminosities could be in error by a factor of 2. Nevertheless, the linear sizes and separations of regions A–C, their [O III] luminosities of 5–11 × 10^{40} ergs s^{-1}, and their [O III]/Hβ ratios are similar to the expected properties of giant H II regions ionized by hot stars (Peimbert and Spinrad 1970; Smith 1975; Elmegreen and Elmegreen 1983).

Our observations do not, however, permit us to conclude that regions A–C are locally ionized H II regions. Bergeron *et al.* have already shown that the total [O III] $\lambda\lambda$4959, 5007 luminosity and the high-excitation conditions generally prevailing throughout the emission-line region are consistent with photoionization by the continuum radiation from the active nucleus. Assuming a line-of-sight depth of regions A–C equal to their projected length, the power-law continuum from the quasar nucleus can be shown to be still capable of supporting the observed [O III] fluxes. We have therefore considered the possibility that regions A–C are density enhancements of the gaseous envelope which are ionized by the quasar continuum emission, rather than locally ionized by hot stars. Assuming normal heavy-element abundances, the observed [O III]/Hβ ratios for regions A–C indicate densities in the range $n = 1$–5 cm^{-3} on the basis of the photoionization models of Ulrich and Péquignot (1980).

A possible explanation for the origin of the inhomogeneities of the gaseous envelope is an apparently recent gravitational interaction between the quasar and galaxy G1, which lies some 40″ (75 kpc) to the north of it. Numerical simulations of galaxy-galaxy interactions by Toomre and Toomre (1972), Icke (1984), and others suggest that resulting disturbances dissipate on rather short time scales. Galaxy G1 has the smallest projected separation from MR 2251−178, a radial velocity difference G1−quasar of +1250 km s^{-1} (Bergeron *et al.* 1983), and has both extended radio emission associated with it (Ricker *et al.* 1978) and strong low-ionization optical emission lines (Bergeron *et al.* 1983). We have used the models of Icke (1984) to estimate velocity perturbations in the gaseous quasar envelope induced by a prograde, coplanar interaction between a disk system and a galaxy of comparable mass, in an attempt to assess the effects of such an encounter. Following Icke (1984), we assume $v_{\rm pert} \sim 4\pi g v(R/b)^3$, where v is the circular velocity in the perturbed galaxy, b is the impact parameter, R is the characteristic radius of the galaxy at which $M(R) = 0.5M(\infty)$, and the dimensionless constant $g = 0.39$. We have taken a lower limit of $R = 20$ kpc, $v = 200$ km s^{-1}, and arbitrarily taken $b = 50$ kpc, giving $v_{\rm pert} \sim 60$ km s^{-1}, considerably larger than the expected local sound speed. We have no satisfactory way of estimating b, but we conclude that shocks may have occurred in the gaseous disk, assuming plausible parameters for an interaction between the quasar and galaxy G1. If this interpretation is correct and galaxy G1 lies behind the quasar (a critical prediction which a search for absorption lines in the galaxy spectrum may be able to confirm), then the encounter was prograde, consistent with the model requirements proposed by Icke (1984). There is marginal evidence for an extension of region A–C in the direction of galaxy G1 visible in our [O III]−continuum image, and a slightly deeper exposure could confirm or refute its existence. Interaction models frequently predict countertidal features on the far side of the interacting nuclei, and this could explain the diffuse emitting regions seen to the SW of the nucleus.

To derive an estimate of the time elapsed since the interaction, we note that the optical emission-line spectrum of galaxy G1 can be reproduced assuming photoionization by the quasar continuum and average interstellar densities if the true separation between the quasar and galaxy G1 is at least 5 times the projected separation of 75 kpc (Bergeron *et al.* 1983). However, the spectrum of galaxy G1 closely resembles that of low-ionization H II regions, suggesting that a recent burst of star formation within the galaxy, possibly associated with the tidal encounter, may have occurred. The minimum-separation argument of Bergeron *et al.* nevertheless remains valid, providing a lower limit to the projected separation of the galaxy and the quasar, and hence a lower limit to the time elapsed since the interaction of 2 × 10^8 yr. Furthermore, if we assume, on the basis of the estimated cluster size (Phillips 1980), an upper limit to the line-of-sight separation between the quasar and galaxy G1 of 500 kpc, this interaction took place within the past 4 × 10^8 yr.

The idea that quasars are activated by interactions between galaxies, especially within small clusters where stripping and virialization have occurred more slowly than in large clusters, has been discussed by Stockton (1982), Bothun *et al.* (1982), Hutchings and Campbell (1983), Stockton and MacKenty (1983), and others. Indeed, Hutchings and Campbell (1983) have already drawn attention to the possible interaction between MR 2251−178 and galaxy G1 on the basis of their detection of extended emission between them in red light centered on Hα, although the correspondence between their results and those reported here requires confirmation.

Precisely how such encounters could initiate the quasar activity is not well understood, it being rather unlikely that an interaction of the type considered for MR 2251−178 could produce sufficient disturbances in the inner regions to be responsible for activating the nucleus directly. On the other hand, a model for the channeling of material into the nuclear regions of barred spiral galaxies has been proposed by Tubbs (1982), and further observations could decide whether such a model could apply in the case of MR 2251−178. Models of Seyfert activity have also considered the possibility of an interaction between the nucleus and the associated galaxy disk, largely inspired by the peculiar appearance of certain classical Seyfert galaxies, especially the frequent presence of faint annular structures (Adams 1977; Heckman, Balick, and Sullivan 1978; Simkin, Su, and Schwarz 1980). For MR 2251−178 the full width at zero intensity of the Balmer lines measured by Canizares, McClintock, and Ricker (1978) of between 18,000 km s^{-1} and 23,000 km s^{-1} for Hβ and Hα, respectively, would be consistent with the DR (inner disk and outer ring) morphological classification of Su and Simkin (1980) using their reported correlation between the full width at zero intensity of the Balmer lines and disk structure found for Seyfert 1 galaxies. This correlation has been interpreted by Su and Simkin as an indication that the line broadening is related to the mechanism of material infalling into the nucleus. The high X-ray luminosity of MR 2251−178, L_x(2–10 keV) = 10^{45} ergs s^{-1} (Ricker *et al.* 1979), is also consistent with this DR structure on the basis of the correlation found between morphological type and X-ray intensity by Su and Simkin (1980).

For the region within 10″ from the nucleus, the nonlinearity of the instrumental intensity transfer function, the variable seeing conditions, and our limited spectral coverage do not permit us to make detailed studies of the morphological, kinematic, and ionization conditions there. We nevertheless have evidence for knots and possible filamentary structure extending to the NW of the nucleus, reminiscent of the instability condensations seen around dominant galaxies in X-ray clusters (e.g., Heckman 1981), although condensation of the line-emitting gas may have been triggered by inflowing material associated with the underlying galaxy rather than with the surrounding cluster.

In summary, our observations, taken in conjunction with the kinematical data from Bergeron *et al.* (1983), confirm that the quasar MR 2251 − 178 resides in the center of an envelope, or disk, of ionized matter rotating around the quasar. A recent gravitational interaction between galaxy G1 and the quasar or quasar progenitor may have been responsible for shocks within the envelope leading to density enhancements or possibly star formation in the envelope far from the nucleus. We speculate that this interaction may also have been responsible for the activity within galaxy G1 and, by some as yet poorly understood process, the quasar itself.

Note added in manuscript 1984 February 22.—Since the submission of this paper, we have received the results of further [O III] − continuum observations of MR 2251 − 178 by Hansen, Noorgard-Nielsen, and Jorgensen (1984) with the Danish 1.5 m telescope and the ESO CCD camera. Their results show an almost precise correspondence with the [O III] emission features reported here.

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