

OPTICAL CONTINUUM SIGNATURE OF THE JET IN THE SPIRAL GALAXY NGC 4258

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ABSTRACT

The large spiral nearby SABbc galaxy NGC 4258 has been imaged in the optical continuum using two filters at 5320 Å and 7020 Å with 200 Å bandpasses which are free of emission lines. The color image produced by dividing the two bandpasses reveals an elongated feature at the location of the jet seen in the radio continuum and in H α . The jet seen in the optical continuum appears as a “blue” feature compared to the galaxy bulge. We consider four possible origins for the optical continuum signature of the jet: (1) optical synchrotron radiation, (2) light from the invisible active nucleus scattered by interstellar electrons or dust particles in the channel bored in the interstellar medium by the high-energy particles of the jet, (3) continuum emission from shocks in colliding high-velocity clumps of gas, and (4) a passive mechanism: reduced extinction through the galaxy because of the absence of dust in the jet. It is shown that a combination of the last two effects may be the most likely explanation for the optical continuum observed in the jet of NGC 4258.

Subject headings: galaxies: active — galaxies: individual (NGC 4258) — galaxies: jets — radiation mechanisms: nonthermal — shock waves

1. INTRODUCTION

The nearby SABbc galaxy NGC 4258 has a well-known low-energy jet that was first revealed optically through H α imaging (Courtès & Cruveillier 1961). The jet is sometimes described as “anomalous arms”; we discourage this designation, because it generates confusion about the actual nature of the feature. Van der Kruit, Oort, & Mathewson (1972) found the radio jet in the continuum at 21 cm, and subsequently it became the target of numerous studies; we refer the reader to the works of Martin et al. (1989) and of Cecil, Wilson, & Tully (1992), where numerous references to other works will be found. NGC 4258 has been observed recently in the ultraviolet with balloon-borne FOCA (Courtès et al. 1993), in X-rays by ROSAT (Pietsch et al. 1994), and by ASCA (Makishima et al. 1994). Although the nucleus appears relatively quiet at present, the galaxy has several distinct X-ray emission components including the jet, and an obscured low-luminosity active nucleus. Watson & Wallin (1994) found evidence for a rapidly rotating disk in the nucleus and inferred a central massive object of $10^7 M_{\odot}$. Makishima et al. (1994) propose that weak active galactic nuclei (AGNs), like NGC 4258, are quasars which have evolved into normal galaxies as the gas available to the central mass-accreting black hole decreased. No evidence so far had been found of the jet of NGC 4258 in the optical continuum. We report in this *Letter* the result of CCD imaging of NGC 4258 in continuum light which betrays the presence of the jet.

2. OBSERVATIONS

Observations were carried out using a focal reducer (f/8 \rightarrow f/3.5) on the Mont Mégantic Observatory 1.6 m telescope. Several images of NGC 4258 were obtained in 1994 February with narrowband interference filters in the bright nebular lines (for the purpose of an abundance survey), and in the stellar continuum using two other filters at 7020 and 5320 Å and with broader bandpasses ($\Delta\lambda = 200$ Å) especially designed to

exclude contamination by nebular emission lines. Short-exposure images of the galaxy and of the spectrophotometric standard star Feige 34 were obtained during the night of 1994 May 4–5. The detector used was a Thomson 1024 \times 1024 CCD with a pixel size of 0".7. In this optical configuration, the useful field of view is about 10' in diameter. The field of view was centered about 2.9 north of the nucleus; flat-fielding was achieved using sky flats obtained during twilight. Exposure times were 3 \times 600 s in each of the filters. Throughout this *Letter* we assume a distance of 5.5 Mpc.

Image reduction and analysis were performed with IRAF¹ following usual procedures. Images were divided by high signal-to-noise ratio (S/N) sky flats, and the sky background was subtracted as a constant over the field. Great care was taken to achieve the best spatial registration of the individual images by using GEOTRAN in IRAF; the registration is estimated to be accurate to better than 1/10 of a pixel.

3. RESULTS

We show images of NGC 4258 at 5320 Å with a 200 Å bandpass and at H α in Figures 1 and 2 (Plates L5 and L6). The optical jet is well seen in H α . Martin et al. (1989) and Cecil et al. (1992) have suggested that the optical emission of the jet is probably due to line emission arising from gas of the ambient interstellar medium which has been entrained and shocked by the radio-emitting gas. Figure 3 (Plate L7) shows a “color” image of NGC 4258 resulting from a division of the continuum image at 5320 Å by the image at 7020 Å; light tones correspond to relatively blue colors, and dark is for relatively red colors. The dark patches would correspond to regions of higher extinction; the bluer light tends to come from the star-

¹ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

PLATE L5

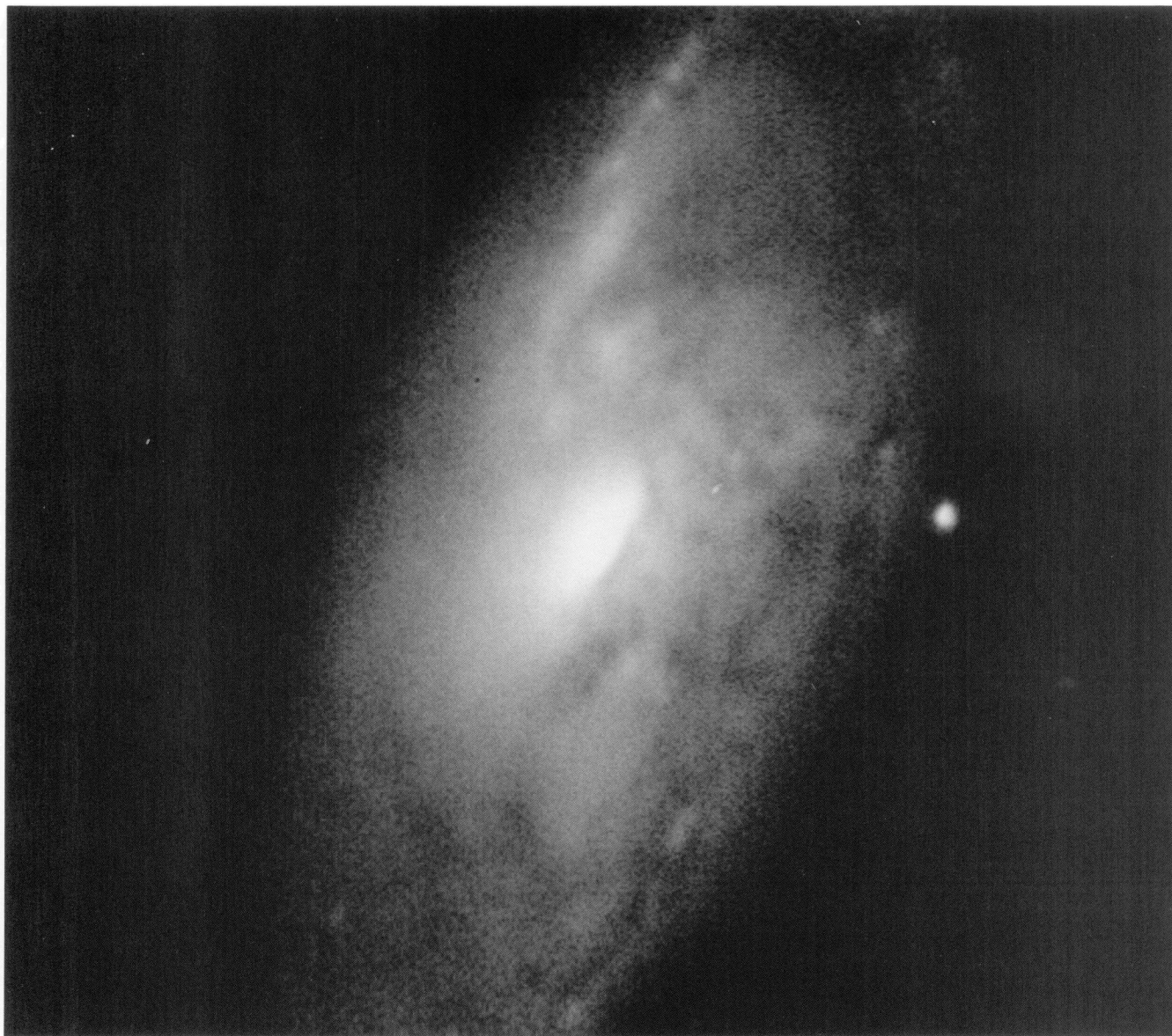


FIG. 1.—Image of the galaxy NGC 4258 in continuum light at 5320 \AA with a 200 \AA bandpass. All figures are from images obtained with the Mont Mégantic 1.6 m telescope; north is at the top, and east is at the left. The size of the field shown is approximately 5.7×5.0 .

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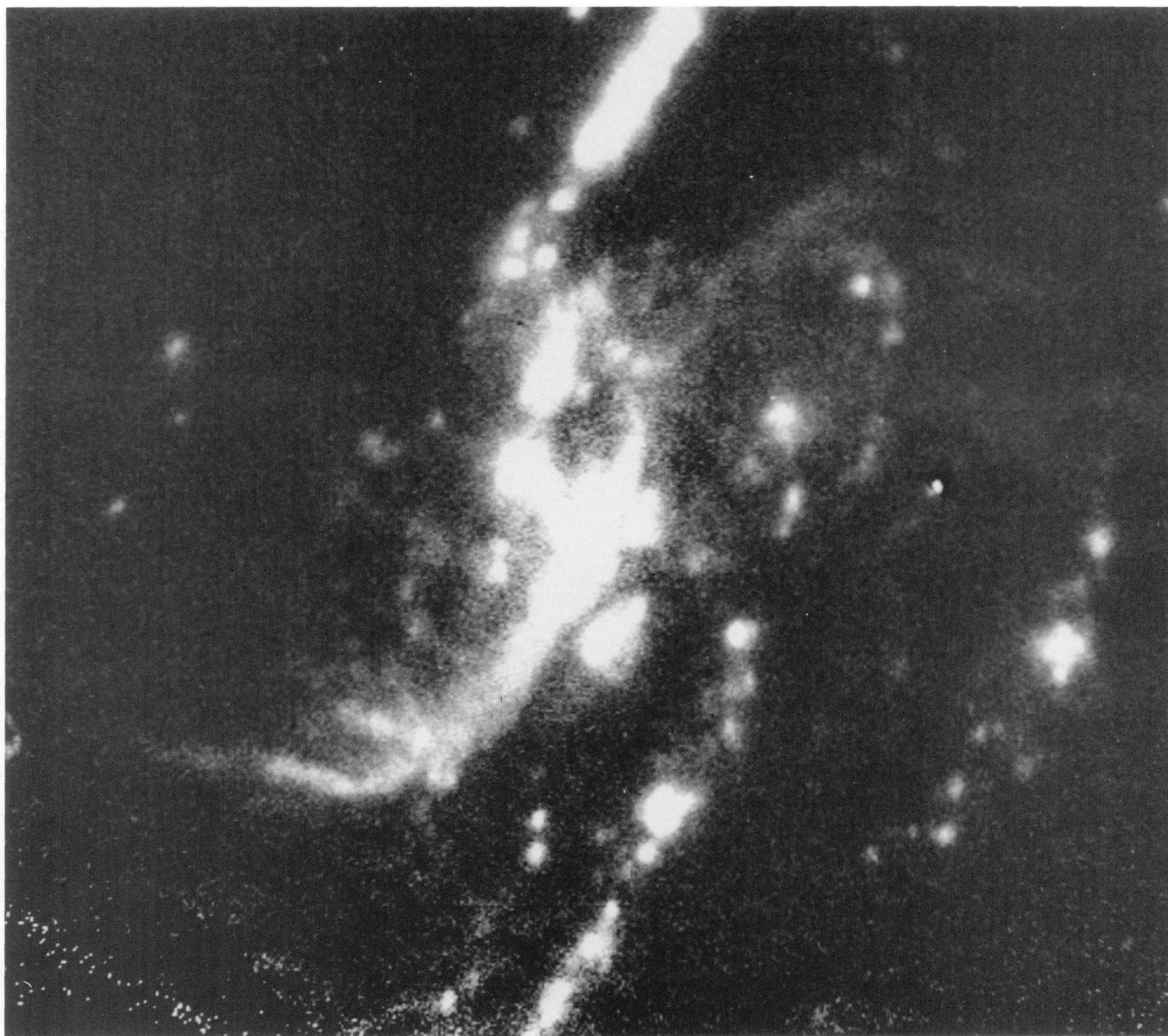


FIG. 2.—H α image of NGC 4258 obtained with a narrowband filter ($\Delta\lambda = 10 \text{ \AA}$) tuned to 6574 \AA . The star formation regions are visible in the spiral arms. The jet is the elongated feature crossing the nucleus at a position angle of about 147° , and splitting into two fingers about $1''.25$ from the nucleus. The parameters of the image are as in Fig. 1.

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PLATE L7

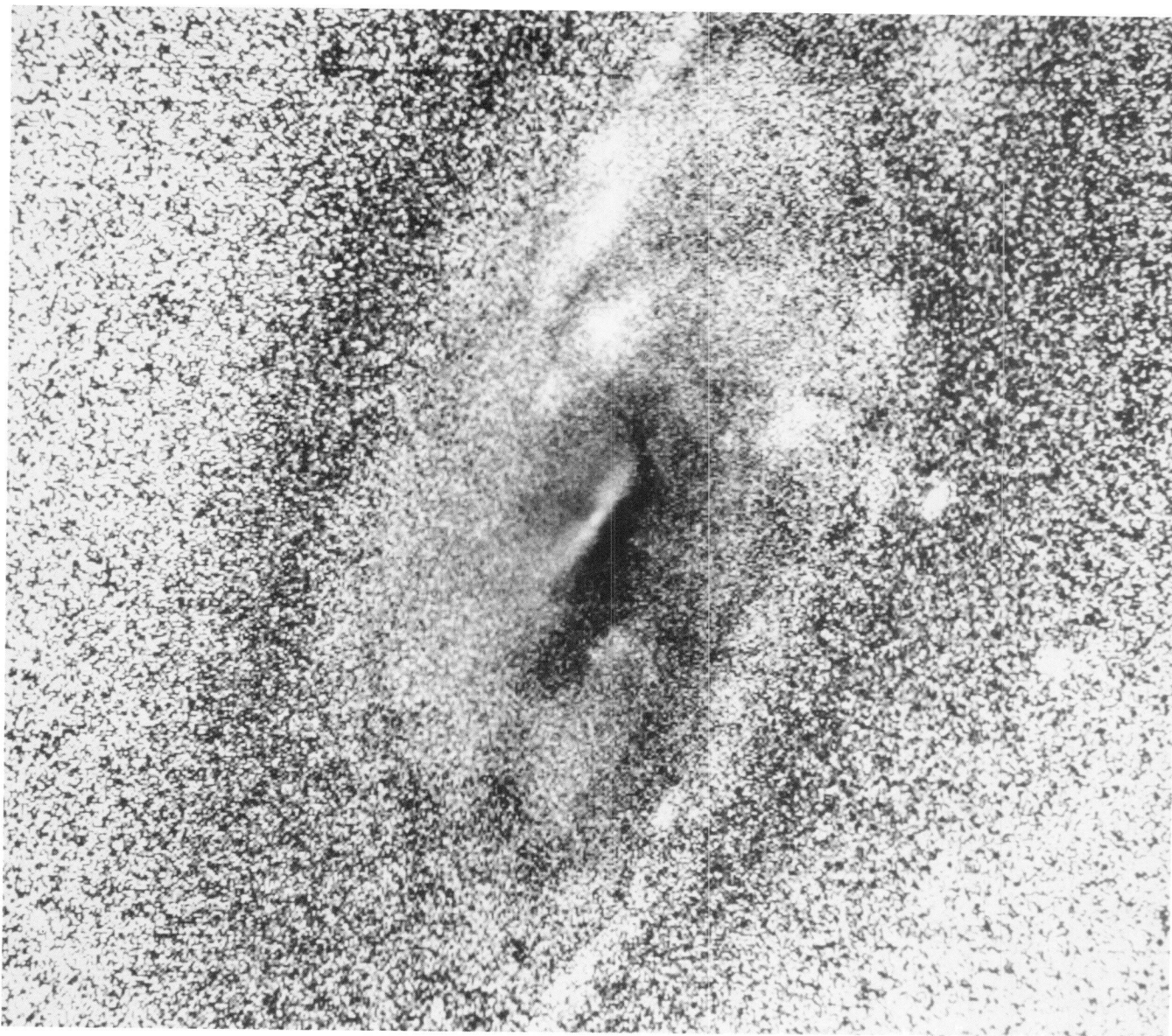


FIG. 3.—Color image of NGC 4258 resulting from the division of the image at 5320 Å by the one at 7020 Å. The parameters of the image are as in Fig. 1.
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forming regions in the spiral arms of the galaxy (Fig. 2). The "redder" central regions are closely associated with the nuclear CO complex discussed by Martin et al. (1989) and Plante et al. (1991) as seen in Figure 4a (Plate L8).

Examination of Figure 3 reveals an elongated blue patch resembling a ridge crossing the nucleus, with redder regions on either side. This blue ridge corresponds to the location of the jet; it has a shape reminiscent of the central radio and optical jet seen at H α , but it looks more diffuse and regular than the latter. We show enlargements of the central region in Figures 4a and 4b (Plate L9). The low-energy jet of the spiral galaxy NGC 4258 is seen in the optical continuum as an enhanced blue feature.

What we observe is probably a mix of continuum light from the normal disk and bulge stellar population plus an apparent light excess related to the jet. It is very difficult with the present imaging technique to derive a color index for the jet component only; this would require area spectroscopy. We exclude contamination by the very few nebular lines falling within the filter bandpass at 5320 Å with a 200 Å bandpass; possible contaminating nebular lines are [N I] λ 5199 and [Fe III] λ 5270, but their intensity is usually only 0.2% of H β ; they would require unrealistically large equivalent widths to contaminate the measured continuum flux to the level observed.

The area over which the color excess is seen corresponds to about $30'' \times 6''$. We find a 10%–20% excess flux seen at the jet position when subtracting the image in the red from the one in the visual, using the surface brightness of the bulge as a reference. Over the 200 Å bandpass, this represents a total excess flux of about 1.2×10^{-12} ergs cm $^{-2}$ s $^{-1}$ or an equivalent mean surface brightness of $\sim 3 \times 10^{-17}$ ergs cm $^{-2}$ s $^{-1}$ Å $^{-1}$ arcsec $^{-2}$ over the same bandpass. This corresponds to an excess luminosity for the whole central jet of about 4×10^{39} ergs s $^{-1}$ in the 200 Å bandpass.

4. DISCUSSION

Daly (1992) has provided an excellent review of the possible sources of ultraviolet and optical continuum radiation originating from extragalactic jets. She discusses inverse Compton scattering of microwave background photons with relativistic electrons, thermal bremsstrahlung emission, Thomson scattering of anisotropic radiation from the AGN, and synchrotron radiation. However, the physical conditions and environment of the jet in NGC 4258 are highly different from those of high-redshift extragalactic jets. For example, using the observed parameters of nonthermal radio emission of the jet of NGC 4258 (Krause, Beck, & Klein 1984; Hummel, Krause, & Lesch 1989), we can immediately exclude optical continuum arising from inverse Compton scattering; predicted optical fluxes are well below detection.

We consider four possible origins to explain the blue continuum excess associated with the jet in NGC 4258:

1. It could be due to intrinsic continuum emission from the jet, such as synchrotron radiation. A way to verify this hypothesis would be measurement of optical polarization. A search for optical polarization in NGC 4258 has already been done by Roy, Arsenault, & Noreau (1985); it led to an upper polarization limit of 5% at the location of the jet.

The synchrotron radiation intensity varies according to $I \propto \nu^{-\alpha}$; the spectral index $\alpha = 0.7$ and the total flux at 10.7 GHz (0.157 Jy) have been measured in NGC 4258 by Krause et al. (1984). Extrapolating this flux to 5200 Å with $\alpha = -1.0$ (the

spectral index that Krause et al. recommend at high frequencies) gives 3×10^{-6} Jy or 3×10^{-29} ergs cm $^{-2}$ s $^{-1}$ Hz $^{-1}$. Multiplying this by the 200 Å (2.2×10^{13} Hz) bandwidth of our filter gives a total flux of 6.7×10^{-16} ergs cm $^{-2}$ s $^{-1}$. Since only the inner parts of the jet would contribute, the associated flux would be a fraction of the latter value, that is, several order of magnitude below the observed flux related to the optical excess.

2. A second origin for the blue continuum excess is light emitted by the AGN being scattered by interstellar electrons (Fabian 1989) or by dust particles in a channel bored by the jet. First, we derive a general expression for the expected intensity of scattered light. Let us approximate the monochromatic luminosity of AGN as $L_\lambda = 4 \times 10^{40}$ ergs s $^{-1}$ /10000 Å = 4×10^{36} ergs s $^{-1}$ Å $^{-1}$ (Makishima et al. 1994); this is an upper limit, because most of the AGN energy is radiated in the X-ray and UV domains. Furthermore, we suppose that extinction between the AGN and the scatterers is negligible. The emission coefficient of diffused light per unit volume per unit solid angle at a distance r from the nucleus is

$$j_\lambda(r) = \frac{n_s \sigma_s L_\lambda}{16\pi^2 r^2},$$

where n_s is the number density of the scattering particles and σ_s is the effective cross section of the scatterer. If the distance to Earth of the scatterers is D , this is further reduced by a factor $(r/D)^2$. Thus the expected observed intensity of the scattered light is

$$I_\lambda(r) = \frac{L_\lambda}{16\pi^2 D^2} \int_0^L n_s \sigma_s dl,$$

where the units of $I_\lambda(r)$ are ergs cm $^{-2}$ s $^{-1}$ Å $^{-1}$ sr $^{-1}$. For electrons we use $n_e = 100$ cm $^{-3}$ in the ionized medium of the jet; $\sigma_e = 6.65 \times 10^{-25}$ cm 2 is the Thomson scattering cross section. At $D = 5.5$ Mpc, the width of the feature corresponds to 160 pc, i.e., $\int_0^L dl = 5 \times 10^{20}$ cm. For a bandpass of 200 Å, we derive $I_e(r) \sim 10^{-26}$ ergs cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$. Since the observed excess is of the order of 6×10^{-15} ergs cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$ in that bandpass, scattered light by interstellar electrons cannot account for the observed excess.

For dust particles, we make further simplifying assumptions: we suppose that multiple scattering removes the strong forward dependence of the phase function of light scattered by dust particles, making scattering isotropic; in practice this function is complicated (cf. Spitzer 1978; Yusef-Zadeh, Morris, & White 1984). The cross section for dust particles is $\sigma_d = A_\lambda C_\lambda$, where $A_\lambda \sim 1$ is the albedo and $C_\lambda = 7 \times 10^{-10}$ cm 2 . From Osterbrock (1989) and Doyon, Puxley, & Joseph (1992), we estimate $n_d \sim 10^{-10}$ cm $^{-3}$ based on a gas-to-dust mass ratio of 150, $\rho_d = 3.3$ g cm $^{-3}$, and $n(\text{H}) = 100$ cm $^{-3}$. With other parameters being the same as for electrons, the above equation leads to $I_d(r) \sim 10^{-22}$ ergs cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$. Again this is several orders of magnitude smaller than observed. Consequently, we exclude AGN light scattered by interstellar electrons or dust particles as the origin of the observed blue excess.

3. The observed X-rays and the high values found for the [N II]/H α ratio are indicative of shocks (Martin et al. 1989; Cecil et al. 1992). Shock waves with velocities of several 100 km s $^{-1}$ can produce strong flux of EUV and soft X-ray radiation which can photoionize the surrounding gas, thus producing the lines and continuum emission. We have used the results of the models of Sutherland, Bicknell, & Dopita (1993) predicting

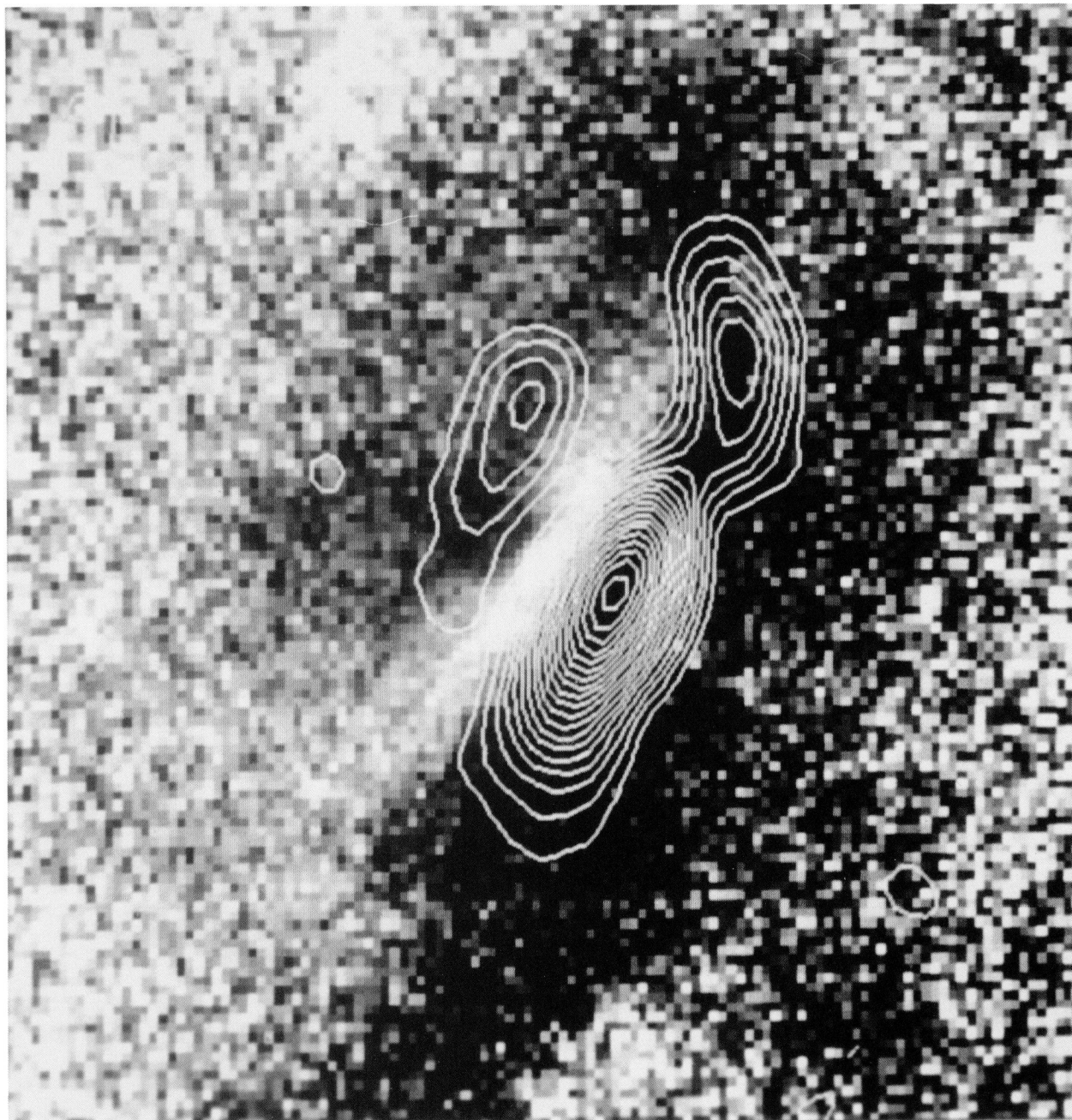


FIG. 4a

FIG. 4.—Close-up of the galaxy center: (a) superposition of the CO contour map of Plante et al. (1991) on the $v - r$ color map; (b) $v - r$ contours superposed on the H α image. The plus sign marks the optical center of the galaxy. These images are $1'.4 \times 1'.4$.

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PLATE L9

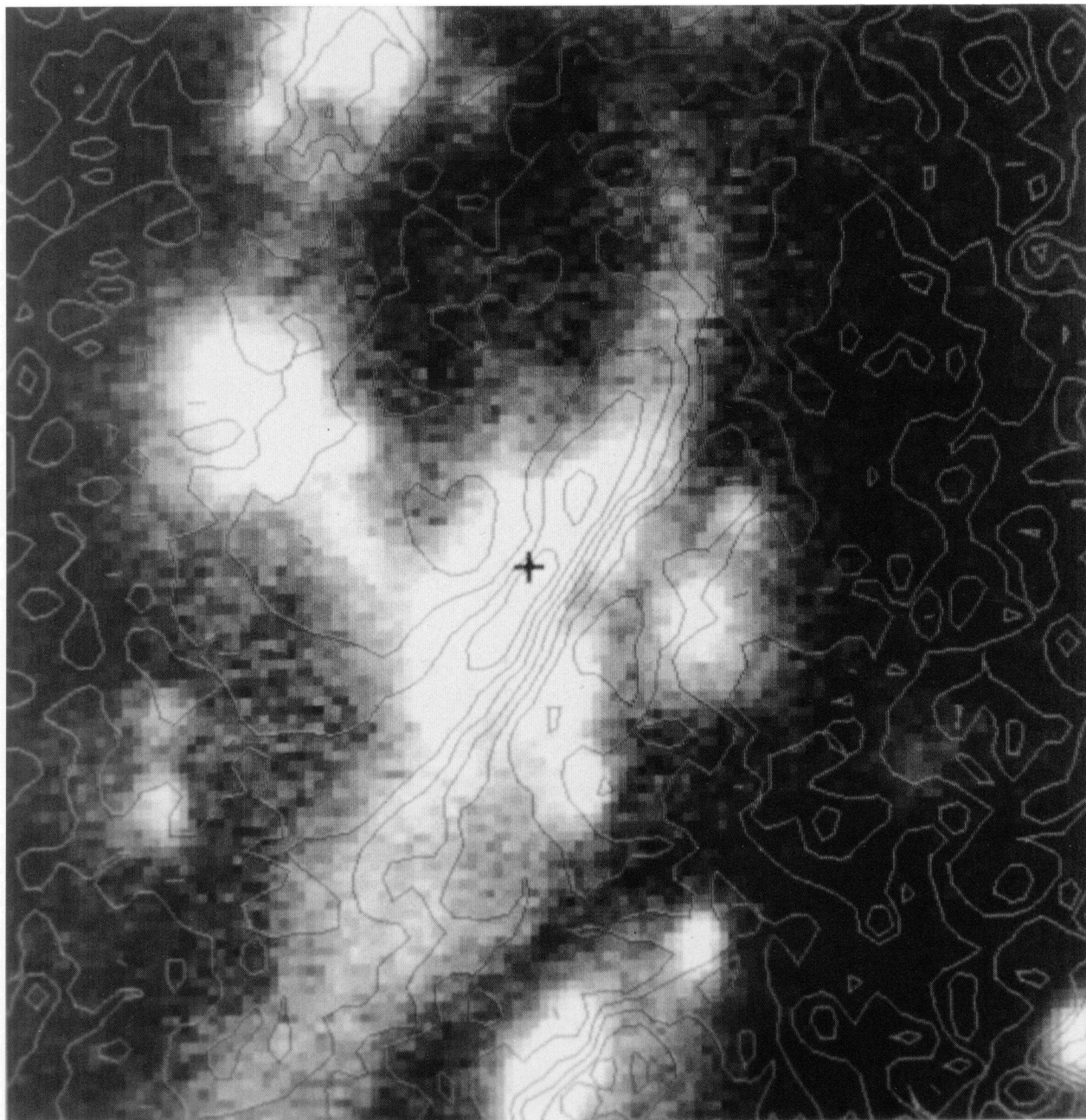


FIG. 4b

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continuum and line fluxes produced in cloud-cloud collisions. Their model is as follows: outflowing plasma from the radio source interacts with dense molecular clouds of different density and produces a turbulent supersonic velocity field in the gas which is ablated from the dense cloud through the Kelvin-Helmholtz instability. The clumps collide with each other at supersonic speeds and produce strong shocks which radiate a large fraction of their internal energy in the extreme ultraviolet and X-ray domain. There is both a high excitation photoionized spectrum from the precursor gas, and a low-excitation gas from the dense gas. The underlying continuum is a variable component made up of free-bound and two-photon emission at low velocities, becoming dominated by free-free emission from a range of temperatures at high velocities.

For colliding clouds of density $n_1 = 1 \text{ cm}^{-3}$ and $n_2 = 10 \text{ cm}^{-3}$, and shock velocity of 450 km s^{-1} , the models of Sutherland et al. (1993, their Fig. 7) predict a continuum emission of $10^{-19} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \text{ arcsec}^{-2}$. This is lower than observed, but with higher densities the predicted flux could approach what we observe (cf. § 3). Although Sutherland et al. (1993) cannot predict how their model evolves at higher density, one can reasonably assume values n_1 and n_2 several times higher than the above in the center of NGC 4258; this could push the predicted optical continuum flux at least an order of magnitude higher. Moreover, the predicted flux at 1–2 keV ($\sim 3 \times 10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \text{ arcsec}^{-2}$) is consistent with the *ROSAT* observations. The *ROSAT* map does not resolve the jet, but the central emission region observed by *ROSAT* in the “hard2” (0.91–2.01 keV) appears elongated in the direction of the radio and optical jet (Pietsch et al. 1994, their Fig. 3); this was also pointed out by Cecil et al. (1992). Pietsch et al. (1994) derive a total 0.1–2.4 keV flux of $3 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ for the central region, assuming that the emission mechanism is bremsstrahlung; a good fraction of this must originate from the jet itself.

4. The smoothness of the optical continuum blue signature contrasts with the clumpy structure of the jet at H α . Some other effect must be at work. To investigate this, we assume that the jet lies very close to the plane of the disk were most of the interstellar dust is expected to be. As proposed by Martin et al. (1989), energetic cloudlets have bored a tunnel through the interstellar material. Interstellar gas has been shocked and ionized, and dust has been destroyed or evacuated. A direct consequence is that one can see to larger geometrical depths into the bulge of NGC 4258 when looking along lines of sight crossing the jet: one gets more galaxy light, and, because it suffers less extinction, it is bluer than the rest of the bulge at equivalent galactocentric distances.

To test this hypothesis, we have measured the color index at several locations in and around the jet using a square aperture of $3''.5 \times 3''.5$; we call our bands at 5320 \AA , “ v ,” and at 7020 \AA , “ r .” These locations (col. [2] of Table 1) are given in arcseconds with respect to the jet axis (which is close to the line of nodes of the galaxy) at position angle of 147° . For comparison, the color index $v - r \simeq -1.07$ of the northern arm star-forming regions is slightly *bluer* than that of the jet, $v - r \simeq -0.92$. We then make the assumptions that the brightness distribution of the starlight in the absence of extinction is intrinsically symmetric about the nucleus, and that the dust is foreground. We compare only symmetrically located points to reduce the effect of the surface brightness variations of the galaxy which is inclined by $i = 72^\circ$ with respect to the plane of the sky. Looking at Table 1, the nucleus is at $+00+00$, and

TABLE 1
COLOR INDEX OF THE JET

POINT (1)	POSITION		$v - r$ (mag) (4)	$F(5300 \text{ \AA})^b$ (5)
	Location ^a (arcsec) (2)	Remark (3)		
A	+00+21	North of C on the jet	−0.75	5.4
B	+00+11	North of C on the jet	−0.88	14
C	+00+00	Nucleus	−0.92	54
D	+00−11	South of C on the jet	−0.88	18
E	+00−21	South of C on the jet	−0.82	7.8
F	−14+00	East of C off the jet	−0.79	8.1
G	+14+00	West of C off the jet	−0.75	5.3
H	+07+00	West of C off the jet	−0.59	5.6
I	−07+00	East of C off the jet	−0.75	17
J	+00+25	North of C on the jet	−0.85	9.5
K	+00+05	North of C on the jet	−0.90	26
L	+00−05	South of C on the jet	−0.92	39
M	+00−25	South of C on the jet	−0.86	11

^a See text.

^b Units of flux are $10^{-17} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1} \text{ arcsec}^{-2}$.

+00+21 is on the jet but 21" north of the nucleus; −07+00 is 7" east of the nucleus, and +07+00 is 7" west of the nucleus; etc. We assume that the intrinsic surface brightness of the galaxy should be the same at each point of a given pair, and that differences in color $v - r$ arises mostly because of differences in the local dust extinction.

Assuming that the bluer color observed in the jet is due to a difference in extinction, we used a Galactic law of extinction (cf. Osterbrock 1989) to compute equivalent differential extinctions, ΔA_v ; these are listed in column (3) of Table 2. We then measured on the v image at 5320 \AA the difference in v flux for the same pair of points. Column (4) of Table 2 gives the excess flux expressed in v magnitude between the members of each pair. Comparison of columns (3) and (4) shows that there is a rough trend where a larger ΔA_v corresponds to a larger Δv ; however, Δv is always larger than ΔA_v .

If the jet has evacuated the dust, the color index we measure in the jet may approach the true color of the stellar populations of the bulge. But what is the color of a dust-free bulge? To simulate this condition, we observed the edge-on galaxy NGC 891 through our set of filters. We measured the $v - r$ color as a function of the distance above the plane of the galaxy, where we assume the effects of reddening by dust to be minimized. The color of the bulge becomes bluer higher up above the plane: $v - r$ varies from 0.5 at 6" above the plane to −0.32 at 54" above the plane. Obviously the color of a dust-free bulge is much redder than the color at the location of the jet in NGC 4258. Consequently, dust evacuation in the galactic

TABLE 2
INFERRED EXTINCTION AND OBSERVED BRIGHTNESS ENHANCEMENT

Pair (1)	Position (2)	ΔA_v (3)	Δv (4)
A & E	North minus south on the jet	0.23	0.41
B & D	North minus south on the jet	−0.06	0.22
F & G	West minus east off the jet	−0.14	−0.44
H & I	West minus east off the jet	0.51	1.18
J & M	North minus south on the jet	0.03	0.18
K & L	North minus south on the jet	0.06	0.45

plane can contribute to increase the continuum stellar flux along the lines of sight crossing the jet, but it is insufficient; the color of the jet is too blue to be explained solely by dust evacuation. Although viewing through a bulge face-on compared to edge-on will result in a different color index because of the various distributions of different stellar populations, we feel that an additional source of blue light is needed to explain the optical continuum feature associated with the jet in NGC 4258. The most likely source is shock excitation as described in item 3 above.

We held stimulating discussions with Pierre Martin and Luc Binette. We thank René Racine, who suggested, some years ago, a search in the optical continuum of the jet of NGC 4258. Raymond Plante kindly provided an electronic version of the CO map of NGC 4258 obtained with the Owens Valley interferometer. The referee made several helpful remarks. This research was funded by the Natural Sciences and Engineering Research Council of Canada and by the Fonds FCAR of Québec.

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Note added in proof.—Shortly after this Letter was accepted, G. Cecil, A. S. Wilson, & C. De Pree (*ApJ*, 440, 181 [1995]) published the results of their *ROSAT* X-ray observations of NGC 4258. The *ROSAT* HRI images reveal a structure strongly reminiscent of the optical continuum feature we report here. Cecil et al. propose that hot shocked gas along the jet is producing the X-rays.