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X-RAY AND OPTICAL OBSERVATIONS OF MCG–6-30-15

F. J. PINEDA,[1] J. P. DELVAILLE, J. E. GRINDLAY,[2,3] AND H. W. SCHNOPPER
Harvard-Smithsonian Center for Astrophysics

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ABSTRACT

X-ray and optical observations of MCG–6-30-15 show it to have an X-ray luminosity of $L_x \approx 10^{43}$ ergs s^{-1} and an X-ray–optical ratio of $L_x/L_{\rm opt} \approx 3$. We confirm the original classification of a Type 1 Seyfert with FWZI (Hβ) $\gtrsim 6500$ km s^{-1}. We derive a power law from the infrared and optical flux ($\alpha \approx 2$) which is in good agreement with the optical continuum power law. If the power law is extrapolated to ionizing UV, we find insufficient UV radiation to excite the Balmer lines, implying either collisional excitation or more UV radiation than expected from the power law. The Balmer decrement is consistent with either an optical absorption $A_v \approx 1.7$ or, more likely, collisional excitation.

Subject headings: X-rays: sources — galaxies: Seyfert — galaxies: nuclei

I. INTRODUCTION

4U 1325–31 has been identified with MCG –6-30-15 on the basis of a 5 day observation with the rotating modulation collimator (RMC) on board the *SAS 3* X-ray observatory in 1976 June (Pineda *et al.* 1978). In the discovery telegram Huchra and Davis tentatively classified the galaxy as a 15th mag Type 1 Seyfert. Since that time MCG –6-30-15 has been observed in X-rays by *HEAO 1* (Marshall *et al.* 1978), which detected no change in intensity, and in the optical by ourselves and others. In this paper we present refined data and report on the results of our optical observations.

II. X-RAY OBSERVATIONS

Evidence for the identification of MCG –6-30-15 with 4U 1325–31 was found during analysis of production data of a 12° × 12° RMC field of view containing this source as well as Cen A and IC 4329 A. Table 1 shows the rates and positions computed from 79 orbits of useful data obtained during the period 1976 June 10–15 with an exposure of $\sim 10^7$ cm^2 s.

The 1 σ upper limit for extent of 0.'4 is consistent with a point source (Delvaille, Epstein, and Schnopper 1978). Figure 1 (Plate 15) shows the region containing MCG –6-30-15 from a CTIO 4 m red plate taken by W. Liller in 1978 April. Superposed around the galaxy is the 90% confidence error circle (radius $\sim 40''$) centered on $\alpha = 13^{\rm h}33^{\rm m}1.^{\rm s}97$, $\delta = -34°2'44''$ which was obtained from a positional analysis of the X-ray data.

The X-ray spectrum estimated from the RMC data is relatively insensitive to cutoff energies in the range 0–2 keV, and we assume a spectrum with zero cutoff in the following calculations.

If the data are fitted with a thermal bremsstrahlung spectrum, we obtain a temperature of 16(+36, –6) keV. If the data are fitted to a power-law energy spectrum $df/dE \propto E^{-\alpha}$, we obtain a spectral index $\alpha = 0.3 \pm 0.2$ and an X-ray flux density of $(24 \pm 7) \times 10^{-30}$ ergs cm^{-2} s^{-1} Hz^{-1} at 10^{18} Hz (4.14 keV). This corresponds to an X-ray luminosity of 10^{43} ergs s^{-1} (2–10 keV) at the redshift distance of 46.5 Mpc (assuming $z = 0.00775$—see below—and using $H = 50$ km s^{-1}Mpc^{-1}).

We find no evidence for time variability. Our observation corresponds to 1.8 ± 0.2 UFU and is in good agreement with the earlier *UHURU* detection of 2.1 UFU (Forman *et al.* 1978) and with the *HEAO* A-2 observation of 2.1 ± 0.3 UFU (Marshall *et al.* 1978).

III. OPTICAL OBSERVATIONS

The optical observations were conducted by J. E. G. at CTIO using the 4 m telescope and Ritchey-Chrétien spectrograph with the SIT vidicon camera. The dispersion was ~5.6 Å per channel and the resolution was ~20 Å in the spectral range 4000–7000 Å. The slit was $2'' \times 10''$ oriented E–W centered on the nucleus. The observation was made on 1978 May 30 in conditions of $\sim 2''$ seeing through 1.05 air masses. The efficiency in each channel was calculated from the spectra of standard white dwarfs (Wolfe 485 A and L930-80) and was used to convert the spectrum to absolute flux units. The exposure was 180 s.

The optical spectrum of MCG –6-30-15 is shown in Figure 2. The spectrum appears typical of a Type 1 Seyfert, displaying broad asymmetric Balmer lines (FWHM ≈ 1700 km s^{-1}), narrow forbidden lines, and Fe II emission. Equivalent widths and line strengths are listed in Table 2. The quoted errors are statistical. In fact, systematic errors due to calibration and line blending may be somewhat larger but probably do not exceed 20%. The line strengths are corrected for an

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[1] Currently at Department of Physics and Astronomy, University of Maryland, College Park.

[2] Visiting Astronomer, Cerro Tololo Inter-American Observatory, supported by the National Science Foundation under contract NSF-C866.

[3] Alfred P. Sloan Fellow.

TABLE 1

DATA FROM 79 ORBITS 1976 JUNE 10–15

Collimator (FWHM)	Energy Band (keV)	Count Rate	α_{1950}	δ_{1950}
MC9 ($4'.5$)......	2–6	0.43 ± 0.04	$13^{\rm h}32^{\rm m}57^{\rm s}.47$	$-34^\circ3'22''.5$
	6–11	0.1 ± 0.07	...	...
MC5 ($2'.3$)......	2–6	0.44 ± 0.04	$13^{\rm h}33^{\rm m}4^{\rm s}.02$	$-34^\circ2'38''.1$
	6–11	0.2 ± 0.03	$13^{\rm h}33^{\rm m}1^{\rm s}.09$	$-34^\circ2'19''.8$

assumed extinction $A_v = 0.36$ caused by material in our Galaxy, and a csc reddening law (Sandage 1972).

The raw data of our optical observation were used to estimate the spectral index of the continuum ($df/dE \propto E^{-\alpha}$). We found $\alpha \approx 3.2 \pm 0.4$ and, after correction for the assumed galactic absorption of $A_v = 0.36$, we obtained $\alpha \approx 2.3 \pm 0.3$. Again the error is probably larger because of uncertainties in the reddening correction. Integration of the corrected spectrum using the standard *UBV* response curves (Allen 1973) yielded $B - V = 0.9$. The nuclear flux integrated over the power law in the range 3000–7000 Å and corrected for the emission lines ($< 10\%$ correction) yields a total optical flux density $\sim 2.7 \times 10^{-26}$ ergs cm^{-2} s^{-1} Hz^{-1} (5000 Å), or a luminosity (at the redshift distance of 46.5 Mpc) $L_{\rm opt} \approx 3.2 \times 10^{42}$ ergs s^{-1}. The corresponding spectral index to connect the optical and X-ray flux densities is $\alpha \approx 1.0$, which is not consistent with either the optical or X-ray spectral indices alone and implies the optical and X-ray continuum spectra have separate origins despite their comparable luminosities.

The redshift calculated from the prominent lines is $z = 0.0082 \pm 0.001$, which is in good agreement with a value found by J. Huchra and M. Davis (1979) of $z = 0.00775 \pm 0.00005$.

The spectrum shows prominent Hα, Hβ, and weak Hγ lines with FWHM corresponding to velocities of $\sim$1500, 1700, and 2000 km s^{-1}, respectively. The full width at zero intensity (FWZI) of the Hβ line is greater than or equal to 6500 km s^{-1}. The resolution of the instrument at Hα corresponds to $v \approx 1000$ km s^{-1}. Hα may be blended with [N II] $\lambda\lambda$6548, 6583, and

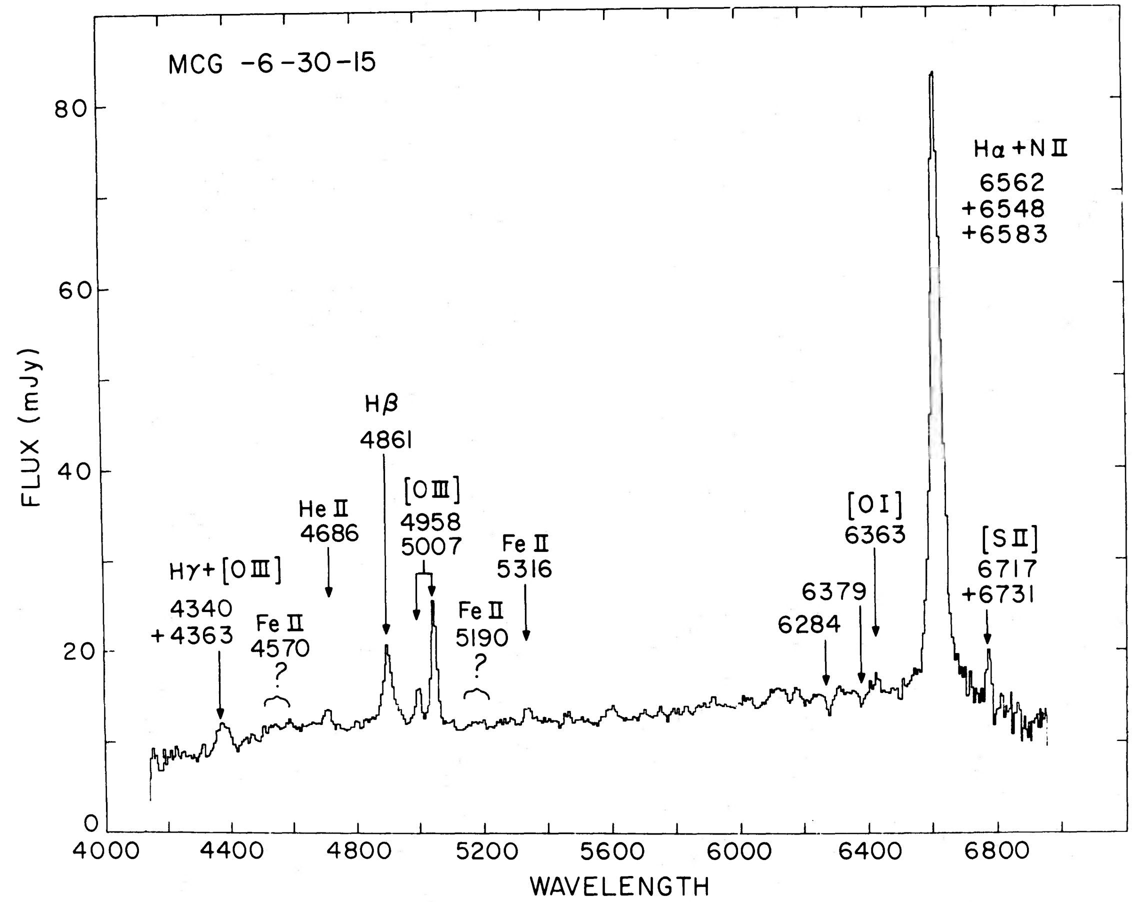

FIG. 2.—The de-reddened optical spectrum of MCG −6-30-15

TABLE 2

TABLE OF EMISSION LINES

Line	λ_0	FWHM (FWZI) Å	Equivalent Width Å	Flux × 10^{-13} ergs cm^{-2} s^{-1}	Relative Hβ
Hγ + [O III]?...	4340 +4363	~30 (75)	9.8 ± 3.2	0.26	0.22
He II...........	4686	~20	4.2 ± 0.6	0.12	0.10
Hβ.............	4861	~30 (≳113)	41.6 ± 2.4	1.2	1
[O III]..........	4958	≲20	11.6 ± 1.6	0.33	0.28
[O III]..........	5007	≲20	28.6 ± 1.2	0.83	0.69
Fe II...........	5316	~20	3.4 ± 1.0	0.1	0.08
[O I]...........	6363	~20	~2.0	≲0.06	≲0.05
Hα + [N II]?...	6562 +6548 +6583	~36 (≳126)	192.6 ± 3.0	6.1	5.08
[S II]...........	6717 +6731	≲20	5.0 ± 2.0	0.14	0.12

NOTE.—Quoted errors are statistical. Systematic errors caused by line blending may be larger. Fluxes are corrected for galactic absorption.

Hγ may be blended with [O III] λ4363. Deconvolution of the assumed instrument response (Gaussian FWHM ≈ 20 Å) from the data suggest that the Hβ line is composed of a narrow spike resting on asymmetric wings which extend mostly towards the red end of the spectrum. Care must be taken in interpreting result, however, since the observed asymmetry could be an artifact of the deconvolution.

The estimated Balmer decrements, corrected for the assumed galactic extinction, are Hα/Hβ = 5.1 ± 0.3 and Hγ/Hβ = 0.22 ± 0.1. Again, the errors are statistical. [O III] λ4363 could account for ~20% of the Hγ flux, and in the extreme case [O III] could account for ~70% of the observed Hγ flux (Osterbrock 1977).

Fe II emission lines at λ5316 and perhaps λ5190 and λ4570 are present in the spectrum. He II λ4686 is also present. These lines are weak, and, although they are probably broad, there is insufficient signal to determine their widths quantitatively. He I λ5876 is absent.

We detect three forbidden lines: [O III] λλ4957, 5007, [O I] λ6363, and [S II] λ6717 + 6731 whose widths are all consistent with being less than or equal to the instrument resolution. The ratio of Hβ to [O III] λ5007 is ~0.7 and is consistent with this galaxy being a Type 1 Seyfert.

Finally, there are several unidentified emission features (e.g., λλ5600, 6150, 6200) as well as two unidentified absorption features at λ6284 and λ6379. The λ6284 absorption line appears to have an equivalent width of ~2.0 Å, but λ6379 is substantially larger than what one expects on the basis of comparison with λ6284 and the correlation (Bromage and Nandy 1973) between galactic absorption and the equivalent widths of λ6284 and λ6379. This correlation would yield $A_v \approx 4.7$ mag, a value not consistent with 21 cm observations of hydrogen column density $N_{\mathrm{H}} \approx 5 \times 10^{20}$ cm^{-2} (Daltabuit and Meyer 1972), nor with optical observations (Fitzgerald 1968) of reddening in our Galaxy. The sodium D lines and other galactic absorption features are also absent. It is therefore possible that the λ6284 absorption feature is due to atmospheric telluric absorption (by O_2), though the equivalent width is much larger than normally observed. The interpretation of the absorption features near λ6284 and λ6379 (or λ6235 and λ6328, if both are within the Seyfert) remains puzzling.

IV. DISCUSSION

The Balmer decrements are steeper than the predicted recombination values, indicating either considerable reddening due to material surrounding the emitting region, collisional excitation within the emitting region, or Balmer self-absorption. If the observed Balmer decrements are due to absorption, we can estimate the amount of reddening intrinsic to the galaxy by de-reddening the decrements using the Whitford reddening curve as parametrized by Miller and Mathews (1972). The theoretical Balmer decrements are nearly independent of electron density and weakly dependent on electron temperature. For this calculation we assume $T = 10^4$ K and $n_e = 10^6$ cm^{-3}. The corresponding theoretical Balmer decrements for case B recombination are Hα/Hβ = 2.81 and Hγ/Hβ = 0.47 (Brocklehurst 1971). Thus, from the Hα/Hβ ratio we calculate an intrinsic reddening $E(B - V) = 0.56 \pm 0.13$. A similar calculation for Hγ/Hβ yields inconclusive but consistent results, since the errors are too large.

The value for $E(B - V)$ given above implies $A_v \lesssim 1.7$ mag. This is sufficiently large that we can expect a low energy cutoff to occur in the X-ray spectrum. Gorenstein (1975) derives an empirical relationship between X-ray absorption and optical extinction using various sources in our own Galaxy and obtains $A_v = 4.5 \times 10^{-22} N_{\mathrm{H}}$. If the interstellar abundances are the same in MCG −6-30-15 as they are in our own Galaxy, then this implies an effective column density $N_{\mathrm{H}} \approx 3.8 \times 10^{21}$ atoms cm^{-2} or an energy cutoff at ~1 keV.

Several authors (Adams and Weedman 1975; Stein and Weedman 1976) have concluded that dust reddening is probably not responsible for the steep Balmer decrements observed in Type 1 Seyfert nuclei, although there may be considerable reddening in Type 2 nuclei. They find no correlation between the Hα/Hβ ratio and the continuum colors, either in the optical or optical versus infrared. On extrapolating the power law derived from the optical and infrared continua, they find that on the average they have sufficient ionizing UV radiation to account for the Balmer line emission in Type 1 Seyferts.

Following their analyses we use a 3.5 μm infrared measurement obtained by Glass (1979), who detected 1.1×10^{-24} ergs $\text{cm}^{-2}\ \text{s}^{-1}\ \text{Hz}^{-1}$. This flux density, combined with our V magnitude of the galaxy, implies a spectral index $\alpha \approx 2$. This is in good agreement with the power law derived from our (de-reddened) optical spectrum. Extrapolating this power law out to ionizing UV and integrating from 228 Å to 912 Å (He and H Lyman limits) we obtain a luminosity ratio $L(\text{UV})/L(\text{H}\beta) \approx 1.8$. This is substantially below the value calculated by Osterbrock (1977) who predicted ~ 14 for pure radiative ionization followed by recombination.

Although this apparent discrepancy may be caused by the large aperture (12″ diameter) used by Glass, it is, in any case, by no means clear that the power law extrapolates as far as the UV range. *IUE* observations of NGC 4151 (Boksenberg *et al.* 1978), for example, clearly show UV emission sufficient to excite the Balmer lines in *excess* of the infrared-optical power law. Furthermore, if the optical luminosity is variable, as seems to be the case with many Type 1 Seyfert galaxies, then the nonsimultaneity of the optical and infrared measurements could cause the observed discrepancy. Finally, if there is considerable nonradiative excitation, e.g., collisional excitation, then this could explain both the apparent lack of sufficient ionizing UV and the steep Balmer decrement. For pure collisional excitation the Hα/Hβ ratio is consistent with an electron temperature $T_e \approx 2 \times 10^4$ K (Van Blerkom 1968). In order not to excite the forbidden-line transitions, this gas would have to have a density $n_e \gtrsim 10^8\ \text{cm}^{-3}$.

The X-ray and 3.5 μm fluxes are consistent with the correlation suggested for Type 1 Seyferts by Elvis *et al.* (1978) as are the X-ray and Hα fluxes. It thus appears that MCG −6-30-15 is rather typical of Type 1 Seyfert X-ray galaxies. However, our results may indicate that the optical spectra in these objects are not excited directly by the X-ray source.

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J. P. Delvaille, J. E. Grindlay, F. J. Pineda, and H. W. Schnopper: Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

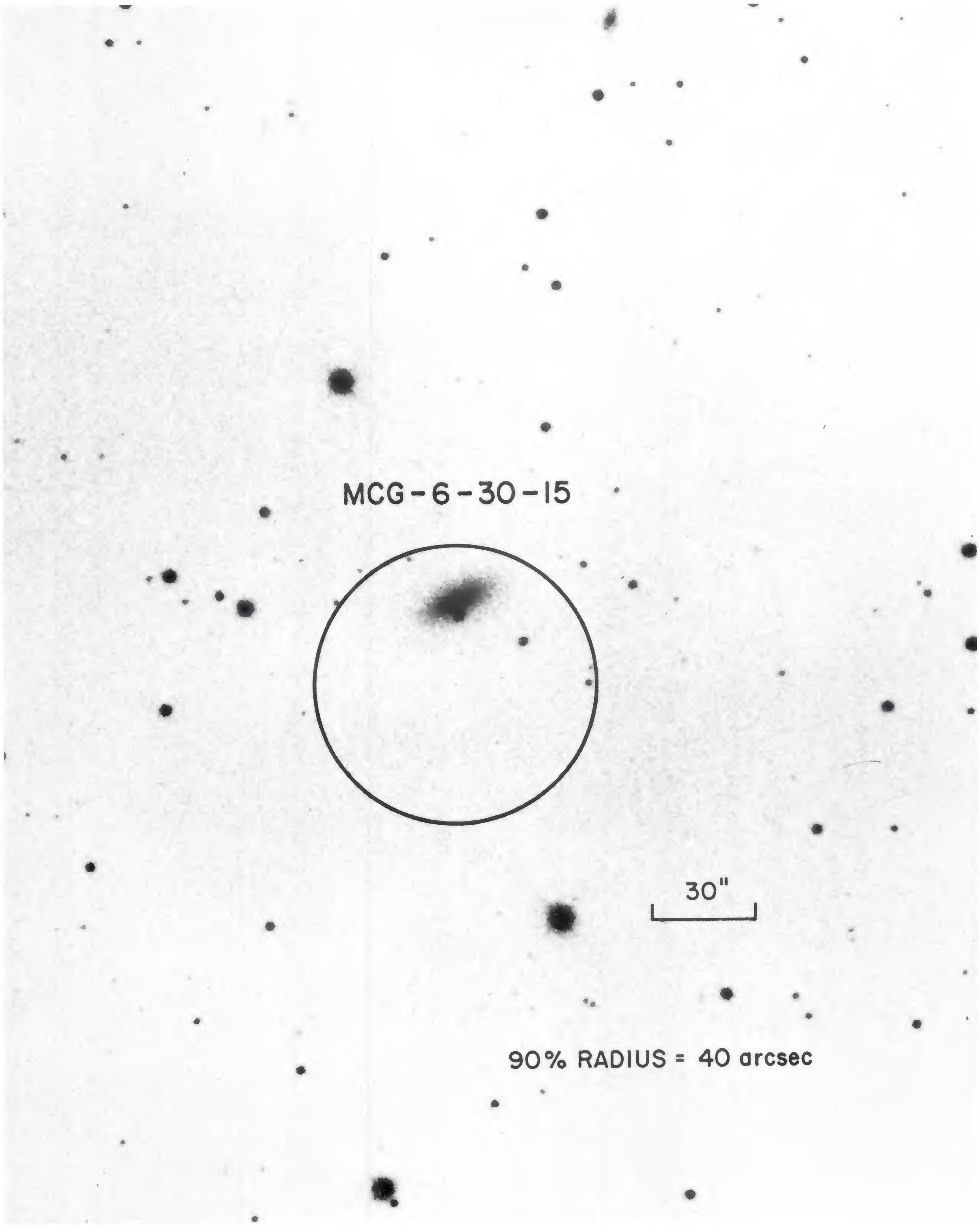

FIG. 1.—The CTIO field containing MCG −6-30-15. The star just south of the galaxy is a normal galactic F star.

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