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HIGH-EXCITATION EXTRANUCLEAR GAS IN THE SEYFERT GALAXY NGC 1068

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ABSTRACT

Optical spectrophotometry of candidate near-nuclear H II regions in the disk of the Seyfert galaxy NGC 1068 indicates the presence of high-excitation extranuclear emission. The optical spectra appear to be very similar to ordinary H II region spectra with the addition of strong lines of [Ne V] λλ3346, 3426 and He II λ4686. We interpret this as the superposition of an H II region spectrum with the high-excitation emission and present theoretical nebular models which suggest that the high-excitation gas is most likely photoionized by a power-law spectrum, probably from the nearby Seyfert nucleus.

Subject headings: galaxies: individual — galaxies: Seyfert — nebulae: general — nebulae: H II regions

I. INTRODUCTION

The bright prototype Seyfert 2 galaxy NGC 1068 has been the subject of a number of recent investigations. For example, Alloin *et al.* (1983) have demonstrated the existence of complex large-scale mass motions near the nucleus, and the impact of such activity on the surrounding galaxy disk has recently been discussed by Atherton, Reay, and Taylor (1985). Nishimura, Kaneko, and Toyama (1984) have illustrated that low-level emission is present over the inner 2–3 kpc of the galaxy, while Telesco *et al.* (1984) have established the presence of a luminous infrared disk covering the inner 3 kpc at a wavelength of 10 μm. In the near-IR Hall *et al.* (1981) have detected shocked molecular hydrogen near the nucleus, and Scoville, Young, and Lucy (1983) have discussed the role of such gas in the process of star formation. Pedlar *et al.* (1983) and Wilson and Ulvestadt (1983) have studied the radio jets emanating from the nucleus and their effect on the surrounding interstellar medium.

In this *Letter*, we report new observations of candidate near-nuclear H II regions, carried out as part of a study of H II region abundances in Seyfert galaxies (Evans and Dopita 1986), which demonstrate the existence of high-excitation extranuclear emission in NGC 1068. We present theoretical nebular models for the data which suggest that the observed emission is a superposition of an ordinary H II region spectrum and emission from a region photoionized by the power-law spectrum emanating from the nearby Seyfert nucleus.

II. OBSERVATIONS AND REDUCTIONS

The optical spectra were obtained under photometric conditions at the 3.9 m Anglo-Australian Telescope on the night of 1983 November 8–9. The Royal Greenwich Observatory spectrograph was used with the Image Photon Counting System (IPCS; Boksenberg 1972) as detector. The instrumental configuration was chosen to give 96 spectra, each separated by 1''.15 on the sky, with a spectral resolution of 8 Å and a spectral coverage of 3200–7400 Å. A slit width of 300 μm (2''.01 on the sky) was employed for these observations. The spectra were reduced to absolute flux in the normal manner (see, for example, Dopita, Binette, and Schwartz 1982), and the spectra of individual knots were obtained by co-adding all the spectra (or spatial increments) in which the knot was detected.

The reddening corrections applied to the observed fluxes were initially determined from the data based on the assumption that the intrinsic Balmer decrement is due purely to recombination for an adopted nebular temperature of 8000 K. The theoretical models computed in § III suggest that a steeper Balmer decrement is more appropriate, and so the reddening corrections were later recalculated on the basis of these models. In some of the spectra, underlying Balmer absorption due to the galaxy is evident, but optical emission is present over the entire region observed, and hence the underlying galaxy continuum could not be accurately subtracted from the total spectra. Consequently, measurements of the emission-line intensities of higher order Balmer lines are somewhat uncertain, and so only the observed $I(\mathrm{H}\alpha)/I(\mathrm{H}\beta)$ ratio was employed to estimate the amount of interstellar reddening.

III. RESULTS AND DISCUSSION

Our observations indicate the presence of a large region of highly ionized nebulosity that extends over a linear dimension of 1.9h kpc at the distance of NGC 1068 ($H_0 = 100h^{-1}$ km s^{-1} Mpc^{-1}), equivalent to 35'' on the sky, along a P.A. of 10° centered on $\alpha = 02^{\mathrm{h}}40^{\mathrm{m}}08^{\mathrm{s}}.4$, $\delta = -00°13'19''$ (1950.0). A typical spectrum is shown in Figure 1. The presence of the high-excitation lines [Ne V] λλ3346, 3426 is immediately evident, and He II λ4686 is visible also. In Figure 2 we plot our observations on the excitation diagram ([Ne V] λ3426/[Ne III] λ3869) versus ([O II] λ3727/[O III] λ5007), together with the data set of Baldwin, Phillips, and Terlevich (1981) for a number of other types of emission-line nebulosity. The crosses indicate the region of parameter space populated by planetary nebulae, while diamonds are used to indicate objects photoionized by power-law spectra. Normal H II regions

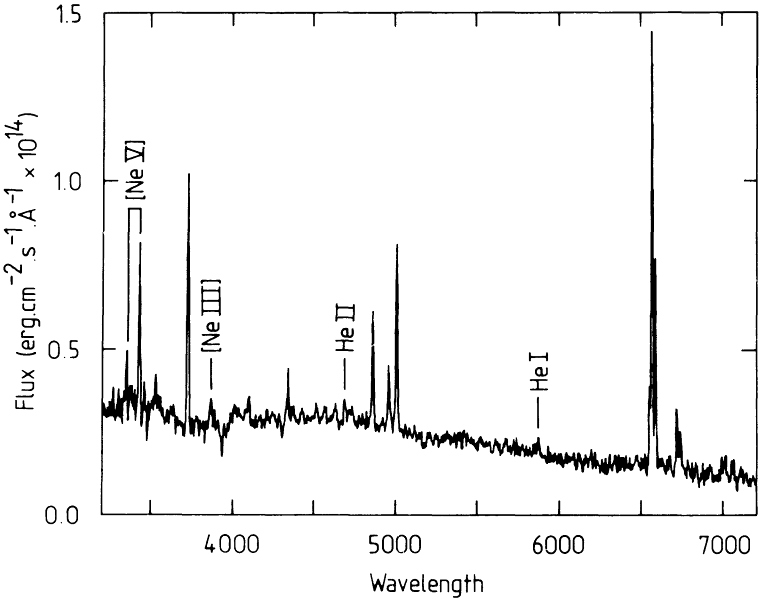

FIG. 1.—A typical IPCS spectrum of one of the knots. Note particularly the high-excitation [Ne V] λλ3346, 3426 and He II λ4686 lines.

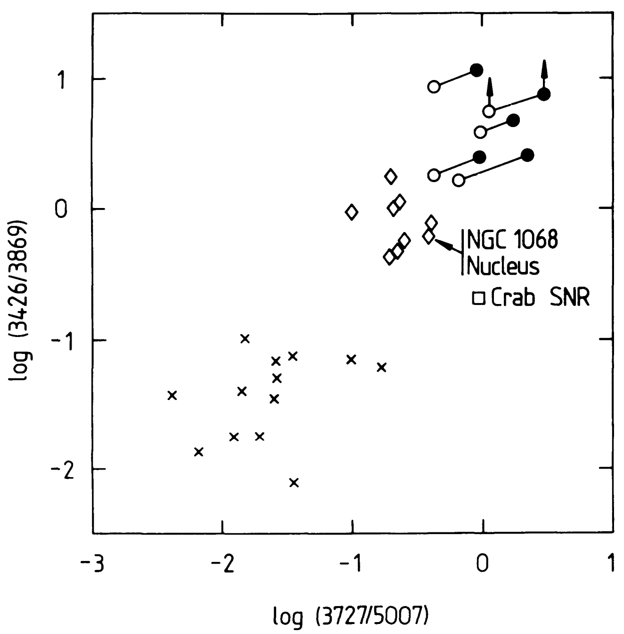

FIG. 2.—The excitation diagram ([Ne V] λ3426/[Ne III] λ3869) vs. ([O II] λ3727/[O III] λ5007). The positions of the observed knots prior to dereddening is indicated by open circles, while filled circles mark the positions after correction for interstellar reddening. Crosses mark the location of planetary nebulae in the Baldwin, Phillips, and Terlevich (1981) sample, and diamonds indicate the positions of objects from the same sample which are photoionized by a power-law spectrum.

and shock-heated objects emit negligible amounts of [Ne V] λ3426. The open circles indicate the location of the knots we have observed, prior to correction for interstellar reddening, while the filled circles indicate the results of applying the reddening correction described above. Inspection of the figure demonstrates the anomalously high [Ne V] λ3426 line intensities from these knots, even before any reddening correction is applied. The apparent ratios of [Ne V] λ3426 to [Ne III] λ3869 are higher in these knots than *any* of the other objects in the Baldwin, Phillips, and Terlevich (1981) data set and are typically 0.8 dex larger than in the nucleus of NGC 1068. On the other hand, the [Ne III] λ3869 line strengths are typical of ordinary H II regions, implying that the neon abundance is not abnormally high. Similarly, the [O III] λλ4959, 5007 line intensities are typical of ordinary H II regions and do not reflect the degree of ionization suggested by the [Ne V] λ3426 line strengths.

When placed on the other excitation diagrams of Baldwin, Phillips, and Terlevich (1981), the knots occupy similar positions to ordinary H II regions, except that I([N II] λ6584)/I(Hα) is typically 0.3 dex larger in the knots than the median values for H II regions. Such a difference is within the scatter for real H II regions and could be readily accounted for by a small increase in nitrogen abundance (Dopita and Evans 1986). From our optical spectra, the knots are atypical of H II regions only in the sense that they show strong [Ne V] λ3346, 3426 and He II λ4686 emission.

It has been well established that [O III] λλ4959, 5007 emission extends outward from the nucleus of NGC 1068 for a considerable distance in the direction of P.A. 30° (Burbidge, Burbidge, and Prendergast 1959; Bertola 1968; Walker 1968). Balick and Heckman (1979) measured strong [O III] λ5007 emission 15″ NE of the nucleus, while Nishimura, Kaneko, and Toyama (1984) detected [O III] λ5007 emission up to 50″ out from the nucleus along the major axis of the galaxy (P.A. 52°).

The presence of extended emission over a very large region to the NE of the nucleus of NGC 1068 raises the possibility that our spectra consist of a superposition of emission from normal H II regions together with emission from a separate region responsible for the high-excitation lines. The resolution of our data is too low to allow us to determine if there are differences in radial velocities or line profiles between the high-excitation and low-excitation lines. However, in this context it is interesting to note that knots showing [Ne V] λ3426 emission appear to follow a spur of "high" (FWHM > 85 km s^{-1}) Hα linewidth with a P.A. of approximately 20°, and located about 10″N and 20″E of the nucleus (Atherton, Reay, and Taylor 1984), although the linear extent of the [Ne V] λ3426 emission is larger than the extent of the spur. Atherton, Reay, and Taylor (1984) interpret regions of high line width as being due to a very high level of turbulent gas motions in the disk due to the activity of the Seyfert nucleus, but the presence of localized high-excitation emission suggests that there may be a contribution from localized activity also.

precludes the possibility that an ordinary stellar source is responsible for photoionizing the high-excitation gas. From a range of models computed using our general purpose modeling code MAPPINGS (Binette 1982; Binette, Dopita, and Tuohy 1985; Evans and Dopita 1985), it would appear that a power-law spectrum is most likely to be capable of producing the degree of ionization necessary to give rise to the strength of the [Ne V] λ3426 emission observed, provided that we assume that the observed spectra consist of a superposition of ordinary H II region spectra and emission from the high-excitation gas. It does not seem to be possible to reproduce both the high-excitation and low-excitation line intensities observed with a plasma photoionized by a single input ionizing spectrum.

To test this hypothesis, we computed a series of theoretical models consisting of the sum of an ordinary H II region and a region photoionized by a power-law spectrum. The summed model spectra were then compared with the *mean* spectrum of the observed knots. The models were homogeneous in the sense that identical elemental abundances were employed for the high-excitation and low-excitation regions, but otherwise the two regions were treated distinctly. The actual elemental abundances employed were determined from the models for the low-excitation region, since the majority of the optical forbidden lines are emitted by that region, and their intensities depend strongly on the adopted abundances. By contrast, the emission from the high-excitation region depends only weakly on the adopted abundances.

The high-excitation region was modeled as a single-zone plane-parallel slab of gas illuminated on one face by a power law with index $\alpha = -1$ (defined by $F_\nu \propto \nu^\alpha$), although the models are relatively insensitive to the assumed spectral index for $-1.5 \lesssim \alpha \lesssim -0.5$. Initially, we employed a power-law spectrum which extended from a turn-on energy of 7.64 eV to a high-energy cutoff of 5 keV. However, with such an ionizing spectrum, we found that it was not possible to reproduce the observed low ratio of I(He II λ4686)/I(Hβ) while simultaneously maintaining sufficiently strong [Ne V] λ3426 emission. Based on the assumption that the Seyfert nucleus is the source of the ionizing photons, we increased the turn-on energy of the power law to 40 ryd in order to simulate the absorption of low-energy photons by the intervening interstellar medium (ISM) and dense molecular clouds observed near the nucleus (Hall *et al.* 1981). Increasing the turn-on energy has the effect of decreasing the number of photons capable of ionizing He^+ [ionization energy $E_I(He^+) = 54.52$ eV] relative to the number of photons capable of ionizing Ne^{+3} [ionization energy $E_I(Ne^{+3}) = 97.11$ eV]. This reduces the intensity of the He II λ4686 recombination line compared to the [Ne V] λ3426 forbidden line. One potential source of [Ne V] λ3426 emission is Auger cascade following *K*-shell photoionization of Ne^{++} with a threshold of ~ 900 eV. The value adopted for the turn-on energy was chosen on the basis of studies of photoelectric absorption of soft X-rays by the ISM (Hayakawa 1973) and the presence of the strong oxygen *K*-edge discontinuity in the absorption cross section at ~ 0.53 keV. Provided that the turn-on energy is substantially greater than $E_I(He^+)$ the value chosen is not critical, and varying it over the range ~ 20–60 ryd has only a small effect on the computed spectrum. The ratio of I([Ne V] λ3426)/(He II λ4686) from the model is then solely determined by the mean ionization parameter in the gas, $\bar{Q}$(H) (defined by Evans and Dopita 1985). The observed ratio of I([Ne V] λ3426)/I(He II λ4686) is achieved when $\bar{Q}(\mathrm{H}) \approx 7 \times 10^8$ cm s^{-1}, and this results in a plasma with a mean electron temperature close to 40,000 K. Such a plasma emits strongly in the [Ne V] λλ3346, 3426, [O III] λλ4959, 5007, and He II λ4686 lines, and the Balmer lines of hydrogen, but little else, in the visible spectrum. Most of the line cooling in the plasma occurs in the very strong O VI λ1034 and He II λ304 UV resonance lines. The density of the high-excitation gas must be considerably lower than the density of the gas comprising the H II region; otherwise, the photon flux from the power-law source would dominate the ionization in the H II region as well, unless the latter were somehow shielded from the central source. If we assume that the power-law spectrum contributes no more than ~ 5% of the ionization within the H II region, then the ratio of ionization parameters in the high-excitation and low-excitation (see below) gas places an upper limit on the density of the high-excitation gas of ~ 0.03 cm^{-3} assuming $N = 30$ cm^{-3} in the H II region. Furthermore, the *mean* density of the intervening column between the nuclear source and the high-excitation gas cannot exceed ~ 0.003 cm^{-3}; otherwise, the observed X-ray luminosity (Lawrence and Elvis 1982) would be incapable of providing sufficient photon flux to ionize the high-excitation region (assuming isotropic emission). Such a low mean density can be achieved by assuming that the ISM is in multiphase pressure equilibrium (Lepp *et al.* 1985, and references cited therein), with the bulk of the gas in the low-density coronal phase. These conditions are expected to hold in the hard X-ray field present near a Seyfert nucleus. However, the mean density of the intervening column may be somewhat higher, ~ 0.01–0.03 cm^{-3}, following recent studies which indicate the presence of a hidden Seyfert 1 nucleus in NGC 1068 which is directing X-ray emission anisotropically in the approximate direction of the high-excitation region (Antonucci and Miller 1985; Krolik and Begelman 1986).

Once the *relative* intensities of the lines emitted by the high-excitation gas have been established, the *absolute* intensity of the emission can be determined by comparison of the predicted intensity of [Ne V] λ3426 with the observed spectrum. The predicted high-excitation contribution can then be subtracted from the observed spectrum in order to estimate the contribution of the low-excitation (or H II region) spectrum to the total emission. The H II region models computed to determine this contribution to the model spectrum were identical in structure to those described by Evans (1986), which should be referred to for a detailed description of the calculations. Suffice it to say here that the H II region was treated as a steady state spherically symmetric nebula consisting of infinitesimal filaments of gas with uniform density of hydrogen atoms plus ions, $N_H = 30$ cm^{-3}, with volume filling factor $\epsilon = 0.1$. The centrally located source of ionizing photons is modeled as a single star with ionization temperature T_{ion}. The stellar atmosphere flux is derived from the log g = 4.0 models of Hummer and Mihalas (1970) using the interpolation scheme developed by Shields and Searle (1978).

Locating the "observed" H II region spectrum on the diagnostic diagrams of Evans and Dopita (1985) suggested that a low $\overline{Q}$(H) ($\sim 3 \times 10^7$ cm s^{-1}) and a high T_{ion} ($\sim$ 56,000 K), together with a metallicity of $\sim \frac{3}{4} Z_\odot$, is required to correctly model the emission. Trial and error led to a final model with 12 + log (O/H) = 8.70, T_{ion} = 60,000 K, and $\overline{Q}$(H) = 1.33×10^7 cm s^{-1}. The He, N, and S abundances were allowed to vary in their ratio to O in order to fit the observations, while the other elements (and in particular Ne) were fixed in their "solar" ratio (Allen 1973) to oxygen. The ionization temperature of the stellar atmosphere required is much higher than the mean found by Evans and Dopita (1985) and employed for their calibration of the H II region abundance sequence (Dopita and Evans 1986). However, one of the knots observed showed a prominent [$\sim$ twice I(Hβ)] broad emission feature centered near 4660 Å, and we identify this as a blend of C III and C IV permitted lines indicative of the presence of WC stars. Such stars would have the effect of biasing the T_{ion} required to model the mean observed spectrum toward a greater temperature than normal.

In Table 1 we present the intensities of the mean observed spectrum of the knots, together with the theoretical contributions of the high-excitation and low-excitation regions according to our models, and the sum of the contributions of the models. The principal model parameters are also presented in the table. Inspection of the table illustrates the excellent agreement between the theoretical models and the mean observed spectrum. Indeed, the only line for which a significant discrepancy exists is [Ne III] λ3869, which is predicted to be a factor of 2 weaker than observed. As described by Evans (1986), this is due to absorption edges in the stellar atmosphere models employed and arises because of our simplistic assumption that the OB associations responsible for producing the ionizing photons which give rise to the H II region

TABLE 1

PHOTOIONIZATION MODELS

A. LINE INTENSITIES

Ion	log I_{obs}	log $I_{high\ exc}$	log $I_{low\ exc}$	log I_{total}
[Ne V] λ3426	+0.09 ± 0.07	+0.10	−11.25	+0.10
[O II] λ3727	+0.35 ± 0.02	−0.98	+0.29	+0.31
[Ne III] λ3869	−0.77 ± 0.09	−2.14	−1.15	−1.11
Hδ λ4102	−0.66 ± 0.03	−0.87	−0.98	−0.62
Hγ λ4340	−0.48 ± 0.03	−0.59	−0.73	−0.35
[O III] λ4363	−1.15 ± 0.51	−1.16	−2.68	−1.15
He II λ4686	−0.83 ± 0.11	−0.84	−4.40	−0.84
Hβ λ4861	+0.00 ± 0.02	−0.22	−0.39	+0.00
[O III] λ4959	−0.27 ± 0.02	−0.48	−0.68	−0.27
[O III] λ5007	+0.19 ± 0.01	−0.02	−0.22	+0.19
He I λ5876	−1.15 ± 0.09	−1.75	−1.26	−1.14
[N II] λ6548	−0.19 ± 0.02	−2.03	−0.21	−0.20
Hα λ6563	+0.51 ± 0.02	+0.32	+0.07	+0.51
[N II] λ6584	+0.26 ± 0.02	−1.56	+0.26	+0.27
[S II] λ6716	−0.34 ± 0.03	−0.89	−0.47	−0.33
[S II] λ6731	−0.47 ± 0.03	−1.04	−0.63	−0.48

B. MODEL PARAMETERS

Parameter	high exc	low exc
T_{ion} K		60,000
α	−1	
$\overline{Q}$(H) cm s^{-1}	7.00×10^8	1.33×10^7
N_H cm^{-3}	0.03	30
ϵ	0.1	0.1
R pc		4.15
He/H	0.082	0.082
12 + log (O/H)	8.70	8.70
12 + log (N/H)	8.19	8.19
O/S	34.4	34.4

NOTES.—Log I_{obs} is the observed logarithmic line intensity relative to Hβ; log $I_{high\ exc}$ and log $I_{low\ exc}$ are the predicted contributions of the models for the high-excitation and low-excitation regions respectively; log I_{total} is the sum predicted line intensities from the models.

contribution to the spectra can be modeled as a single stellar atmosphere with $T_{\rm ion}$ equal to the cluster mean ionization temperature.

On the basis of the agreement between the observed and predicted spectra, we propose that the data can be best explained by a superposition of emission from a normal H II region and emission from a high-excitation region. The high-excitation emission is due to photoionization of gas in an interstellar cloud by the power-law spectrum emanating (presumably) from the nearby Seyfert nucleus. X-ray photons with energies lower than ~ 40 ryd are absorbed by warm ($\sim 10{,}000$ K) interstellar clouds in the intervening ISM, and this may be at least partly responsible for the [O III] λλ4959, 5007 emission observed underlying the central 2–3 kpc of the disk. As pointed out by Atherton, Reay, and Taylor (1985), the active nucleus must also pressurize the interstellar cloud, either through interaction of the radio jets (Blandford and Königl 1979), subrelativistic winds (Krolik and Vrtilek 1984), or radiation pressure (Kippenhahn, Mestel, and Perry 1975), and this must be responsible for the large turbulent line widths which they detect. Such turbulence will enhance the likelihood of star formation in the interstellar clouds, giving rise to the creation of H II regions and further star formation. Whether or not the high-excitation emission is related to interaction of the nearby radio jets with the interstellar clouds cannot be ascertained from our data. High-resolution narrow-band imaging of the central region of NGC 1068 in [Ne V] λ3426 would be useful to delineate the extent of the high-excitation emission and enable us to map the regions photoionized by the (nuclear) power-law spectrum.

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