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RADIO OBSERVATIONS OF II Zw 40

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ABSTRACT

New observations, using the Westerbork synthesis radio telescope at 21 cm in the line and at 6 cm in the continuum of the dwarf galaxy II Zw 40, are presented. The continuum spectrum shows an infrared excess similar to the one found in galactic H II regions. A rough estimate based on the amount of internal absorption indicates a gas/dust ratio of the same order of magnitude as in our Galaxy, but observations in the far-infrared (100–300 μm) are needed to make better estimates.

Subject headings: galaxies: individual — interstellar: matter

I. INTRODUCTION

II Zw 40 is a blue, high-surface-brightness dwarf galaxy containing an emission-line core (Barbon 1969; Sargent and Searle 1970, hereafter SSI) and a more extended H I halo (Gottesman and Weliachew 1972). The core, about 100 pc in diameter for a distance of $6.8h^{-1}$ Mpc (Gottesman and Weliachew 1972, for a Hubble constant of $100h$ km s^{-1} Mpc^{-1}), looks like a giant H II region similar to 30 Doradus and, in common with many galactic H II regions, shows an infrared excess (Rieke and Low 1972), indicating the presence of dust. On the other hand, abundance measurements (Searle and Sargent 1972, hereafter SSII) show that the core is depleted in heavy elements by a factor of 3 or more and suggest that this is a young or newly formed system. It is then of great interest to see how the dust/gas ratio in this system compares with that in our Galaxy. To this end, we present in this paper new radio (both H I and continuum) observations made with the Westerbork telescope and report a previously unpublished infrared measurement by Rieke. We shall also make a preliminary estimate of the dust/gas ratio.

II. OBSERVATIONS

a) *Radio Continuum*

The source was observed in 1972 December by using the Westerbork synthesis radio telescope (WSRT) 5 GHz receiver. The synthesized beam was 6″ (R.A.) by 100″ (decl.). After the visibilities were Fourier transformed to form a map, an unresolved source of 22 ± 4 mJy was found at the position: $\alpha_{1950} = 5^{h}53^{m}04^{s}.8 \pm 0^{s}.14$, $\delta_{1950} = 3°23'10'' \pm 20''$. This flux, together with other continuum measurements, is plotted in Figure 1. The position agrees with that of the optical object and the one previously found at 1415 MHz (Jaffe 1972). The upper limit on the size is consistent with the dimensions of the emission-line core, 3″ × 5″ (SSI).

The previously reported 1415 MHz continuum flux is 10 mJy (Jaffe 1972), but this includes an erroneous correction for line radiation in the continuum band (see § II*b*). Corrected anew, the continuum flux at 1415 MHz is 30.0 ± 0.5 mJy. The spectral index between 1415 and 5000 MHz is then 0.24 ± 0.14, which is consistent with a free-free radiation spectrum from an optically thin gas.

b) *21 cm Line*

In 1972 May we observed the source by using the WSRT 80-channel filter receiver, which yielded velocity measurements from +660 km s^{-1} to +960 km s^{-1} at intervals of 20 km s^{-1}, with a resolution of

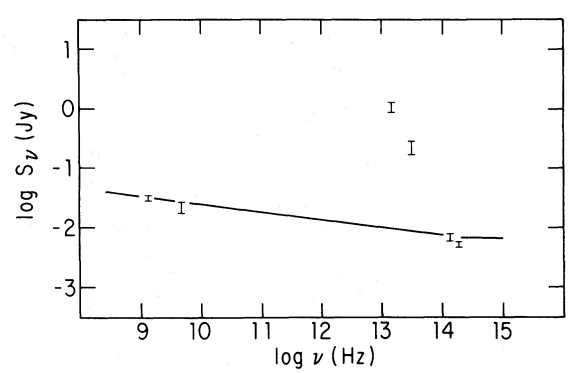

Fig. 1.—Flux measurements of the continuum source. The drawn line is the extrapolation from 1415 MHz of a free-free and free-bound emission spectrum at $T = 2 \times 10^4$ K.

20 km s^{-1}. Spatial resolution was 20″ (R.A.) × 5′.6 (decl.).

The extreme velocity channels showed the presence of the continuum source with a flux of 29 ± 5 mJy, much higher than previously reported. The discrepancy arises because the broad-band result was corrected for line contamination by using the line profile obtained by Chamaraux, Heidmann, and Lauqué (1970) with a low spatial resolution (4′ × 25′), which includes line radiation from a low-surface-brightness halo much larger than our beam (Gottesman and Weliachew 1972). The flux was therefore overcorrected. Using the line data obtained with the same resolution as the continuum observation, we modified the correction and found the 1415 MHz continuum flux quoted above, which is obviously consistent with the value determined from the extreme ends of the line observation.

The line measurements themselves, with the continuum flux removed, are given as a right ascension–velocity map in Figure 2. The contours are of constant antenna temperature, which is a lower bound to the actual brightness temperature, since the source is unresolved in declination. The rms noise is approximately 0.3 K. The map shows a concentration of H I lying about 10″ east of the continuum source and centered at 760 km s^{-1} (heliocentric), and a broader envelope about 40″ across to the east and at a somewhat higher velocity than the peak. The H I distribution is markedly asymmetric with respect to both the line emission region and the continuum source.

The total mass of H I represented in the map is (6.6 ± 1.2) × $10^7 h^{-2}$ $M_\odot$. About half of this is in the unresolved peak and half in the envelope. This galaxy was observed in the line by Gottesman and Weliachew (1972) with slightly lower east-west resolution, but a better north-south one. In addition to an "H I core," which corresponds to the distribution mapped in Figure 2, they found a larger halo, approximately 7′ across, containing about the same mass as the H I core, in each case about (9 ± 1) × $10^7 h^{-2}$ $M_\odot$, essentially consistent with our measurement. Some of this halo is in fact picked up in our beam, which has a large extent in declination. Correcting for this reduces our estimate for the "H I core" to (6.2 ± 1.2) × $10^7 h^{-2}$ $M_\odot$.

If the velocity gradient toward the east were due to rotation, it would imply an angular velocity component of about 100h km s^{-1} kpc^{-1}, but this interpretation seems premature.

c) *Infrared*

II Zw 40 was first detected in the far-infrared by Rieke and Low (1972), who found at 10 μm a flux of 0.22 ± 0.09 Jy. Rieke (private communication) has measured at 20 μm a flux of 1.0 ± 0.2 Jy. These values are plotted in Figure 1 along with near-IR fluxes measured by G. Neugebauer and reported in SSI. The drawn line in Figure 1 is the extrapolation from the radio of the free-free and free-bound radiation spectrum of the hot gas. It is clear that the 10 and

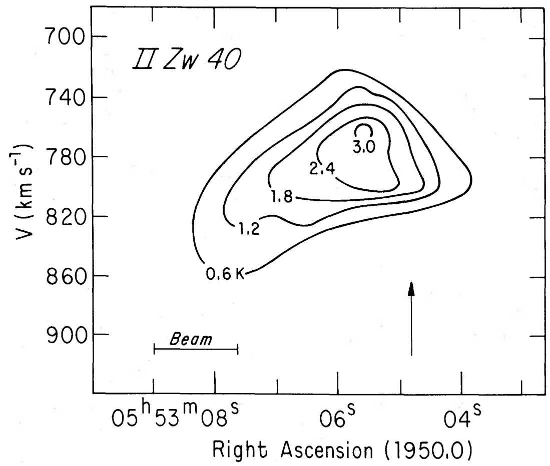

FIG. 2.—Right ascension–velocity map of the H I brightness. The velocities are heliocentric. The contours go in steps of T_a = 0.6 K. The arrow indicates the R.A. of the continuum source.

20 μm fluxes lie well above this line, a feature typical of galactic H II regions, where the excess is evidence of the presence of warm dust. The 10–20 μm color temperature of the dust is 170 or 145 K, depending on whether the emission efficiency varies as λ^{-1} or as λ^{-2}. The points at 1.6 and 2.2 μm lie very close to the extrapolation. This indicates that the attribution by SSI of the near-IR flux to low-mass stars may be erroneous, and they may have overestimated the ratio of low–to–high-mass stars in this galaxy.

III. DISCUSSION

The dust in this object should cause observable extinction, but the analysis of this effect is complicated by its low galactic latitude ($b^{\rm II} = -10°.8$, $l^{\rm II} = 203°.4$), which implies some foreground absorption. SSI in fact found 2.5 mag of extinction at Hβ by using the Balmer decrement, but this assumed only foreground extinction. That this is probably incorrect can be seen from the ratio of the continuum flux to the Hβ intensity, which is $S_{1415}/S_{\rm H I}$ = 1.0 ± 0.15 × 10^{12} s, about 30 times larger than that expected from an H II region if $T = 10^4$ K, and 22 times larger if T is near 2 × 10^4 K, as suggested by Bergeron (1977). Assuming all the continuum emission to be thermal free-free emission from the ionized gas would indicate an extinction at Hβ close to 3.5 mag, but such a value would give a bad fit to the Balmer decrement. An alternative is a mixture of foreground absorption (both galactic and intrinsic) and internal absorption. If the internal absorption is well mixed with the line emission, the Balmer decrements given in SSII, plus our continuum measurements, yield foreground and internal absorptions at Hβ of 1.2 ± 0.2 mag and 11 ± 1 mag, respectively, assuming a Whitford extinction law. Details of the calculation are given in the Appendix. These correspond to A_V = 0.8 mag and 8 mag, respectively. The internal value is probably an underestimate because, in the case of nonuniform absorbing material, we preferentially receive radiation from regions where the absorption is lower than average.

Our extinction solution, designed to fit the same Balmer decrement as the one used by SSI, yields essentially the same corrections for other line ratios as does their solution. Hence it does not alter the conclusions of SSII about abundance ratios or those of Bergeron (1977) about the gas temperature. However, their estimates of the absolute Hβ emission and hence of the number of ionizing photons will be low by a factor of at least 2–3.

The galactic portion of the foreground extinction can be estimated from the local H I column density of $(2.5 \pm 0.1) \times 10^{21}$ cm^{-2} in the direction of II Zw 40 (Heiles 1974). This implies $E_{B-V} = 0.4$, or $A_V = 1.2$ mag (Heiles 1975). The foreground absorption is thus consistent with being totally due to interstellar matter in our own Galaxy.

We can make a rough estimate of the gas-to-dust ratio by using the estimate of absorption internal to the H II region plus our continuum measurements. The electron density deduced from the radio continuum emission from the core is $130h^{1/2}$ cm^{-3}, assuming a uniform gas at $T = 2 \times 10^4$ K. On the other hand, the local electron density in the region cannot exceed 10^3 cm^{-3} from the [O II] doublet $\lambda\lambda$3727, 3729 (Bergeron 1977). Therefore a lower bound of 0.17 can be put on the clumpiness factor. The ratio of visual extinction to column density A_V/N_H in this volume is then at least $1.5 \times 10^{-22}h^{1/2}$ mag cm^3, compared with typical galactic values of about 6×10^{-22} mag cm^2 (Heiles 1975). The validity of the comparison depends on the dust having similar optical properties to galactic dust.

A better estimate of dust content could be made from the IR spectrum. Experience with galactic H II regions indicates, however, that the bulk of the emission lies in the 100–300 μm range where as yet no information exists for II Zw 40. Lacking this, we can conclude only that if the dust is similar chemically and in particle size to that in better-studied H II regions, its abundance relative to hydrogen is probably not less than 25% that found in our Galaxy.

We wish to thank Dr. Rieke for providing us with the 20 μm measurement. The WSRT is operated by the Netherlands Foundation for Radio Astronomy and is funded by the Dutch Organization for Pure Research (Z.W.O.).

APPENDIX

BALMER LINE CALCULATIONS

Notation.—Square brackets such as $[\alpha/\beta]$ stand for $\ln(S_\alpha/S_\beta)$, where S_μ is the flux in the Hμ line. A superscript 0 as in S^0 or $[\alpha/\beta]^0$ refers to quantities that would have been measured in the absence of absorption. The notation $\tau_\mu{}^e$ is the external absorption optical depth in Hμ ($\mu = \alpha, \beta, \ldots$), and $\tau_\mu{}^i$ the internal optical depth. We let subscript R refer to radio continuum fluxes.

For a plane-parallel model of emission, with well-mixed absorption:

$$S_\mu = S_\mu{}^0(\exp - \tau_\mu{}^e)[1 - \exp(-\tau_\mu{}^i)]/\tau_\mu{}^i \qquad \text{for } \mu = \alpha, \ldots, R\,. \tag{A1}$$

We assume a Whitford law so $\tau_\mu/\tau_\beta = \lambda_\beta/\lambda_\mu \equiv r_\mu$, and we assume $\tau_\mu{}^i \gg 1$ for all μ except the radio.

The normalizing to Hβ and taking natural logs:

$$[\mu/\beta] = [\mu/\beta]^0 - (r_\mu - 1)\tau_\beta{}^e - \ln r_\mu \qquad \text{for optical } \mu \tag{A2}$$

or

$$\tau_\beta{}^e = ([\mu/\beta]^0 - [\mu/\beta] - \ln r_\mu)/(r_\mu - 1)\,. \tag{A3}$$

Having got $\tau_\beta{}^e$ we estimate $\tau_\beta{}^i$ with the presumably unattenuated radio flux. Equation (A1) then yields

$$(S_\beta/S_R) = (S_\beta{}^0/S_R)\exp(-\tau_\beta{}^e)/\tau_\beta{}^i\,, \tag{A4}$$

or

$$\tau_\beta{}^i = (S_\beta{}^0/S_R)/(S_\beta/S_R)\exp(-\tau_\beta{}^e)\,. \tag{A5}$$

TABLE 1

BALMER SERIES CALCULATIONS

Quantity	α	δ	γ
(1) r_μ..............	+0.741	+1.120	+1.185
(2) $\ln r_\mu$............	−0.30	+0.11	+0.17
(3) $[\mu/\beta]^0$..........	+1.08	−0.73	−1.30
(4) $[\mu/\beta]$ (SII)........	+1.08	−0.67	−1.24
(5) $[\mu/\beta]$ uncorrected	+1.68	−0.95	−1.67
(6) $\tau_\beta{}^e$.............	+1.16	+0.92	+1.08
(7) $[\mu/\beta]$ predicted....	+1.67	−0.97	−1.67
(8) $[\mu/\beta]$ predicted for $\tau_\beta{}^e = 3.5$........	+1.91	−1.11	−1.89

These formulae are applied to the data in the table whose columns show the individual emission lines and whose rows are: (1) $r_\mu = \lambda_\beta/\lambda_\mu$, (2) $\ln r_\mu$, (3) $[\mu/\beta]^0$ from Kaplan and Pikel'ner (1970) for γ and δ and from SSII for α, (4) $[\mu/\beta]$ as reported in SSII *including* their reddening correction for 2.5 mag absorption at Hβ, (5) $[\mu/\beta]$ *uncorrected* by subtracting 2.3 $(r_\mu - 1)$. (2.3 is 2.5 mag expressed as an optical depth), (6) $\tau_\beta{}^e$ for each line, estimated from equation (A3). The best least-squares value for the three emission lines is $\tau_\beta{}^e = 1.1$, (7) predicted values of $[\mu/\beta]$ using $\tau_\beta{}^e = 1.1$, and (8) predicted values of $[\mu/\beta]$ using 3.5 mag of external absorption at Hβ only.

If we use $\tau_\beta{}^e = 1.1$ and $(S_\beta/S_R) = 0.03(S_\beta{}^0/S_R)$ as reported in the text for $T = 10^4$ K, equation (A5) yields $\tau_\beta{}^i = 10$. For $T = 2 \times 10^4$ K we obtain a value of 7. The errors used in the text are based on the temperature uncertainties and on the reported uncertainties of ± 0.1 in $\log_{10}(S_\mu/S_\beta)$ in SSII.

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