Mon. Not. R. astr. Soc. (1988) **231**, *Short Communication*, 63P–67P

Dark matter in the dwarf galaxy II Zwicky 40

Elias Brinks *European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-8046 Garching bei München, Federal Republic of Germany, and Royal Greenwich Observatory, Herstmonceux Castle, Hailsham, East Sussex BN27 1RP*

Ulrich Klein *Radioastronomisches Institut der Universität Bonn, Auf dem Hügel 71, D-5300 Bonn 1, Federal Republic of Germany*

Accepted 1988 January 22. Received 1988 January 21; in original form 1987 September 21

Summary. H I observations of the Blue Compact Dwarf galaxy II Zwicky 40 at high angular resolution reveal the presence of two kinematical systems. The H I structure and kinematics can be understood in terms of two interacting H I clouds, each cloud consisting of about $2\times10^8 M_\odot$ of neutral gas. The optical emission is located at the centre of the northern cloud and might be the result of recent star formation which is triggered by the interaction. We estimate total masses of order $3\times10^9 M_\odot$ for each cloud. This exceeds the visible mass by an order of magnitude and indicates the presence of dark matter in II Zwicky 40.

1 Introduction

High-resolution observations carried out with the NRAO* Very Large Array (VLA) in the line of neutral hydrogen (H I) have cast new light on II Zwicky 40, a prototypical Blue Compact Dwarf (BCD) galaxy. Since the pioneering work by Sargent & Searle (1970; Searle & Sargent 1972) a number of studies have been devoted to this galaxy at various wavelengths (Gottesman & Weliachew 1972; Jaffe, Perola & Tarenghi 1978; French 1980; Baldwin, Spinrad & Terlevich 1982; Kunth & Sargent 1983; Wynn-Williams & Becklin 1986). In the optical the galaxy shows a bright core with a diameter of about 300 pc, a halo of ionized gas measuring 1 kpc in diameter, and two tails, one extending 2 kpc to the east and a shorter one pointing to the south-east (in this paper we adopt H_0=75 km s^{-1} Mpc^{-1} which puts II Zw 40 at 10.1 Mpc). Also in H I maps published by Gottesman & Weliachew (1972) and Jaffe *et al.* (1978) II Zw 40 shows a core-halo structure. The H I halo is much larger than its optical counterpart and is offset by about 0.5 arcmin from the optical structure. The abundances of heavy elements relative to hydrogen as measured by Lequeux *et al.* (1979) are down by factors of 3–6 as compared to solar values, which indicates that II Zw 40 is young in terms of star-formation history.

*The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under contract with the National Science Foundation.

2 Observations and results

The VLA observations were made on 1985 April 26/27 using the B-configuration which resulted in H I maps with a spatial resolution of about 7 arcsec and a velocity resolution of 10.3 km s^{-1}. A summary of the VLA observations is given in Table 1. The data acquisition, the calibration and reduction procedures will be described in full in a forthcoming paper. The H I data are presented in Figs 1 and 2. The individual H I channel maps can be found in Brinks & Klein (1986). Fig. 1 shows the total H I surface brightness map at full resolution. Fig. 2 shows the velocity field which was derived by taking an intensity-weighted mean of the channel maps after they had been smoothed to a circular beam of 10 arcsec. Assuming, as usual, small optical depth, we derive an H I mass of $3.9\times10^{8} M_{\odot}$ which is in agreement with previous determinations by Gottesman & Weliachew (1972) and Thuan & Martin (1981). This shows that we do not miss any emission due

Table 1. VLA observations of II Zwicky 40.

Field centre α_{1950}	$5^{h}53^{m}00^{s}$
δ_{1950}	3° 24′ 00″
Heliocentric velocity	795 km s^{-1}
Distance	10.1 Mpc
Observing date	1985 April 26/27
Integration time	177 min
Synthesized beam (HPB)	5.9×7.0 arcsec^{2}
Position angle HPB	21°
Velocity resolution	10.3 km s^{-1}
rms sensitivity	1.4 mJy beam^{-1}
Conversion to Kelvin	1 mJy beam^{-1}≡14.7 K

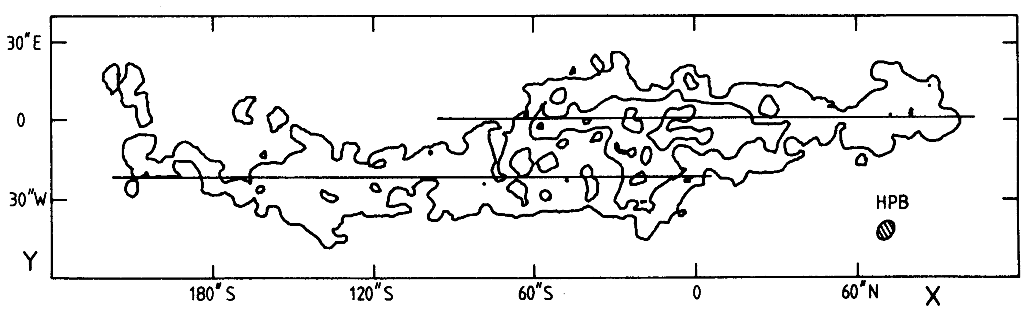

Figure 1. Total H I surface brightness map of II Zwicky 40. Contours are drawn at 5, 30 and 70×10^{20} atom cm^{-2}. The rectangular X–Y coordinate grid is centred on the brightest optical part of II Zwicky 40 and aligned with the H I structure. The position angle of the X-axis is 130°. The two lines indicate the central planes of the two interacting H I clouds. The hatched ellipse corresponds to the size of the beam.

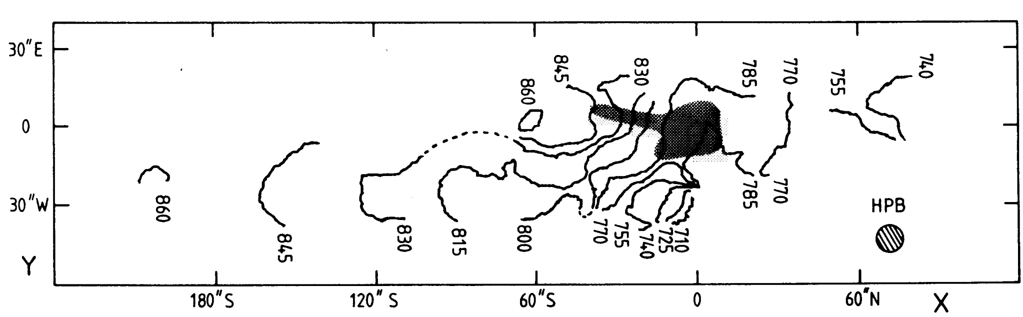

Figure 2. Velocity field of II Zwicky 40 derived from H I data which were smoothed to a circular beam of 10 arcsec. Velocities are in km s^{-1}. The same coordinate grid is used as in Fig. 1. The optical emission coming from II Zw 40 is outlined for comparison purposes. The hatched ellipse corresponds to a circular beam of 10 arcsec.

to an incomplete sampling with the VLA of the shorter baselines. The H I is distributed in a narrow strip, much larger than the optical size of the galaxy, measuring 17 kpc in length versus 2 kpc in width and off-set with respect to the optical emission. The H I velocity field, although complex, is dominated by ordered motions and shows the presence of two velocity-systems.

3 Discussion and conclusions

A possible interpretation of the observed H I distribution and the radial velocities is that we are looking at two interacting H I clouds which are viewed almost edge-on and which partially overlap along the line-of-sight. It should be noted, however, that the interaction which we discuss is on a much larger scale than the merging process which was postulated by Baldwin *et al.* (1982). In Fig. 1 the central plane of each system is indicated by a straight line. The optically prominent part of II Zw 40 finds itself quite naturally at the centre of the northern cloud. Both clouds have about equal amounts of H I mass, $2.1\times10^8 M_\odot$ for the northern versus $1.8\times10^8 M_\odot$ for the southern one. The range of radial velocities observed for each cloud is similar and the clouds share the same sense of rotation. This interpretation is confirmed by inspection of the position–velocity (PV) diagrams presented in Fig. 3 which show clearly the presence of two independent systems. PV plots along the central planes (Fig. 4) show the rotation of each cloud as a function of distance along the plane. In the outer parts the velocity increases linearly with radius. In the area where the clouds overlap along the line-of-sight, the rotation curve steepens.

We dismiss the possibility that one sees one system which spans the full length of the H I structure, i.e. 17 kpc, and another much smaller cloud which is oriented more or less perpendicular to it. Such a geometry would render the H I distribution severely lopsided. Also, the orbits of the H I clouds would have to be non-intersecting to avoid collisions which would give rise to star formation and the rapid destruction of at least one of the systems.

Ignoring the fact that the clouds form an interacting system and assuming that the gas moves in circular orbits, i.e. $M\sim V^2R$, we can estimate the total masses of the clouds. We find $(2.5\pm1.0)\times10^9 M_\odot$ for the northern cloud and $(3.5\pm1.0)\times10^9 M_\odot$ for the southern one, where the error indicates the difference in value obtained for both sides of each cloud. If the two clouds form a bound system one can, following van Moorsel (1987) obtain a lower limit for the total mass of the whole system. A velocity difference of 30 km s^{-1} and a projected separation of 4.7 kpc lead to a lower limit of about $10^9 M_\odot$. These result indicate that most of the mass in the northern and southern cloud is in the form of 'Dark Matter'. Corrected for the fraction of helium we derive a

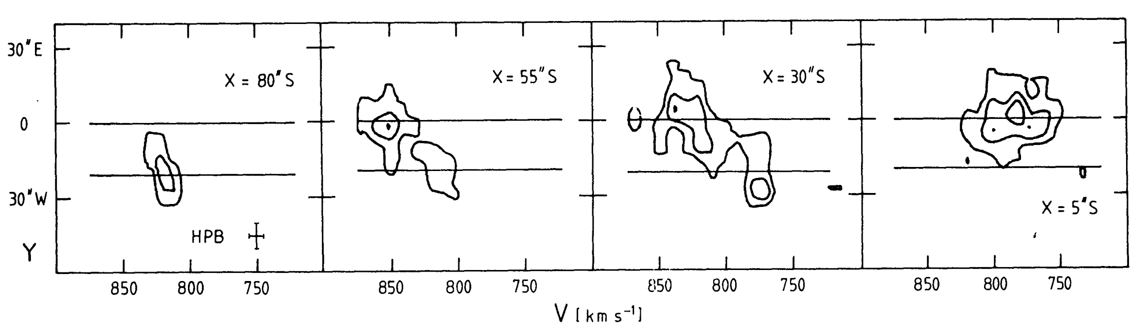

Figure 3. Series of position–velocity maps made perpendicular to and at regular intervals along the H I clouds. The PV maps are made at a position angle of 40°. Contour levels are at 20, 40 and 60 K. The PV maps are based on channel maps which were smoothed to a circular beam of 10 arcsec. The resolution of the maps is indicated by the cross. The location of each PV map is indicated on each frame by its X coordinate. The lines at Y=0 and Y=21 arcsec west indicate the location of the central plane of the northern and the southern cloud and correspond to the lines shown in Fig. 1.

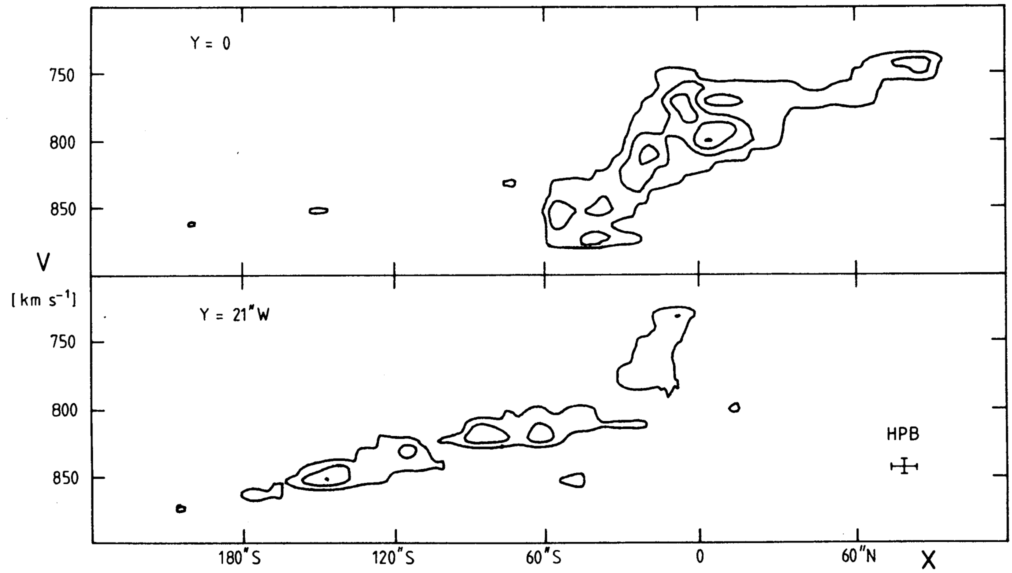

Figure 4. PV maps made along the central plane of the northern cloud (Y=0) and the southern cloud (Y=21 arcsec west), i.e. along the lines shown in Fig. 1. This corresponds to a position angle of 130°. Contour levels are as for Fig. 3.

mass in neutral gas for the northern cloud of $2.8\times10^8 M_\odot$. II Zw 40 has recently been detected in CO by Tacconi & Young (1987). They derive a mass in H_2 of about $3\times10^7 M_\odot$ within a 45-arcsec beam centred on the optical counterpart. It cannot be ruled out that more CO is present in the outerparts of II Zw 40. Also, uncertainties in the conversion formula might underestimate the total amount of molecular material by an order of magnitude. Searle & Sargent (1972) estimate a total mass of ionized gas of order $5\times10^6 M_\odot$. The stars which were produced by the recent burst contribute another 2×10^7 (Baldwin *et al.* 1982) to $10^8 M_\odot$ (Wynn-Williams & Becklin 1986). This adds up to a total of at most $5\times10^8 M_\odot$ in visible material as compared to an estimated total mass of $2.5\times10^9 M_\odot$. For the southern cloud we infer a total mass based on the kinematics of $3.5\times10^9 M_\odot$ and derive a mass in neutral gas of just $2.4\times10^8 M_\odot$. This difference between the two mass determinations can not simply be accounted for by an older stellar population. If one assumes that M/L=6 which is typical for an old disc population (van der Kruit & Freeman 1986), a mass of $3.3\times10^9 M_\odot$ would correspond to an apparent visual magnitude, including 2.5 mag of foreground extinction (see e.g. Lequeux *et al.* 1979) of $m_{\rm vis}\approx15$ mag. Even in the unlikely situation that the stars are distributed as the H I cloud, this would lead to surface brightnesses of typically 23 to 24 mag arcsec^{-2} which would make them easily detectable. Using the method employed by Carignan (1985) we can, assuming that the rotational velocities are completely due to the mass distribution of a dark isothermal halo component, derive a value for its central density. We find within the estimated errors a value which is the same for both clouds, namely $0.004\pm0.0005 M_\odot$ pc^{-3}.

A proof for the correctness of our interpretation would be to find an optical counterpart for the southern cloud. Preliminary inspection of a set of narrow band CCD frames of the southern cloud in the line of Hα revealed no optical emission, nor did an examination of the *IRAS* point source and small extended sources catalogues. II Zw 40 itself is listed as an *IRAS* source. The violent star formation which is seen is confined to the central part of the northern cloud and could have been triggered by the interaction between the two clouds. Deep surface photometry might show the presence of an older stellar population in the northern cloud which could explain at least part of the missing mass, and also reveal an optical counterpart for the southern cloud.

Acknowledgments

We thank the staff at the VLA and especially Dr J. van Gorkom for help with the H I observations and the calibration. We have benefited from many stimulating discussions with Drs B. Pagel and R. Terlevich and comments on an earlier version of this manuscript by Dr J. Wall. UK is grateful for financial support by the Deutsche Forschungsgemeinschaft.

References

Baldwin, J. A., Sprinrad, H. & Terlevich, R., 1982. *Mon. Not. R. astr. Soc.*, **198,** 535.

Brinks, E. & Klein, U., 1986. *Star Forming Dwarf Galaxies and Related Objects,* p. 281, eds Kunth, D., Thuan, T. X. & Tran Thanh Van, J., Éditions Frontières, Gif-sur-Yvette.

Carignan, C., 1985. *Astrophys. J.,* **299,** 59.

French, H. B., 1980. *Astrophys. J.,* **240,** 41.

Gottesman, S. T. & Weliachew, L., 1972. *Astrophys. Lett.,* **12,** 63.

Jaffe, W. J., Perola, G. C. & Tarenghi, M., 1978. *Astrophys. J.,* **224,** 808.

Kunth, D. & Sargent, W. L. W., 1983. *Astrophys. J.,* **273,** 81.

Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A. & Torres-Peimbert, S., 1979. *Astr. Astrophys.,* **80,** 155.

Sargent, W. L. W. & Searle, L., 1970. *Astrophys. J.,* **162,** L155.

Searle, L. & Sargent, W. L. W., 1972. *Astrophys. J.,* **173,** 25.

Tacconi, L. J. & Young, J. S., 1987. *Astrophys. J.,* **322,** 681.

Thuan, T. X. & Martin, G. E., 1981. *Astrophys. J.,* **247,** 823.

van der Kruit, P. C. & Freeman, K. C., 1986. *Astrophys. J.,* **303,** 556.

van Moorsel, G. A., 1987. *Astr. Astrophys.,* **176,** 13.

Wynn-Williams, C. G. & Becklin, E. E., 1986. *Astrophys. J.,* **308,** 620.