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High Resolution Neutral Hydrogen Observations of NGC 4258

G. D. van Albada and W. W. Shane
Leiden Observatory

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Summary. In this paper preliminary results of 21 cm line observations of NGC 4258 obtained with the Westerbork Synthesis Radio Telescope are presented. Disturbances in both the H I density distribution and the velocity field in the neighbourhood of the anomalous arms tend to support the expulsion model of Van der Kruit *et al.* (1972). Outside the region of the anomalous arms the galaxy behaves like a normal spiral galaxy.

Key words: NGC 4258 — galaxies — 21 cm line

I. Introduction

NGC 4258 (=M 106) is a giant Sbc or SBbc spiral galaxy in the Ursa Major group of galaxies. Its optical nucleus lies at $\alpha=12^{\mathrm{h}}16^{\mathrm{m}}29^{\mathrm{s}}.42$, $\delta=47^{\circ}34'53''.2$ as determined by A. A. Schoenmaker (Van der Kruit *et al.*, 1972; further referred to as KOM). Sandage has determined a distance of 6.6 Mpc (Burbidge *et al.*, 1963). These parameters will be assumed throughout this article.

The galaxy has two anomalous gaseous arms cutting through the normal spiral arms, as observed by Courtès and Cruvellier (1961) in Hα and by KOM in 21 cm continuum. The radio emission of these arms is nonthermal as proved by later observations at 6 and 50 cm (de Bruyn, private communication). In their paper KOM proposed a model with the following general characteristics: Gas is expelled from the nucleus in a cone in the plane of the galaxy with velocities up to about 1500 km/s. As the gas travels through the disk it sweeps up part of the disk gas, is braked hereby and by gravity and acquires angular momentum. This process gives rise to shocks. KOM's exploratory calculations show that the gas will tend to form curved ridges or arms. The gas in these arms will rotate much more slowly than the local circular velocity. The gas within a certain distance of the center will have passed the epicenter of its orbit and be falling inward again. Cooling of the shocked gas will have advanced furthest in the regions closest to the nucleus where the gas with the lowest initial velocities lies.

In this paper some preliminary results of observations in the 21 cm H I-line made with the Westerbork Synthesis Radio Telescope are presented. A description of the instrument can be found in papers by Allen *et al.* (1974) and by Baars and Hooghoudt (1974). General characteristics of the observations and instrumental settings are listed in Table 1. The aim of the H I observations was to give us a better insight into the structure and dynamics of the anomalous arms and their relation to the rest of the galaxy. A comparison of the H I data with the KOM model's predictions should be a first step in this direction. In this paper only a qualitative comparison will be given since the numerical parameters adopted by KOM now appear to require substantial revision.

Table 1. Description of the observations

Observed velocities	40, 80, 120, 160, 180, 200, ..., 780, 800, 840, 880, 920, 960 km/s
Base lines	36 m to 1440 m with increments of 36 m
System temperature	140 K (from Allen *et al.*, 1974)
Average noise in the single channel maps	1.6 K (theoretical)
First grating ring	$20'.3 \times 29'.5$
Half power width of the synthesized beam	$24'' \times 32''$
Half power width of the velocity channels	27 km/s

Only 26 of the 40 observed velocity channels proved to contain a significant amount of line radiation. This was found by convolving the single channel maps to a beam of approximately $70'' \times 70''$ so that regions with a surface brightness greater than 0.8 K could be detected. For each individual velocity channel we determined where the hydrogen, if any, occurred and used only this region from the full resolution map, in order to reduce the noise contribution in combined maps. The remaining 14 channels were used as continuum, thus at the same time adequately compensating for an instrumental error that caused a variation in the zero level over the map. From the total flux in each selected region the value of the missing zero spacing was estimated and added. The results described in this article were all derived from these maps. Further processing of particular displays is described in the figure captions.

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Fig. 1. Total H I contour map superposed on an optical photograph (48″ Schmidt telescope, Hale Observatories, 103a–O + GG 13, courtesy P. C. van der Kruit). Contour intervals are 330 K km/s = 6×10^{20} H atom cm^{-2} (= 1.9×10^{20} H atom cm^{-2} face on) beginning with 330 K km/s. The heavy line through the nucleus is the ridge line of the anomalous arms as derived from KOM's 21 cm continuum map. The crosses indicate the star positions used in matching the contour map to the photograph. A correction for the attenuation of the primary beam has been applied. Due to this and to the use of selected regions from each individual velocity channel the noise over the map is not uniform

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Fig. 2. Radiograph of the total H I map. Further noise suppression has been used to obtain a clearer picture

II. Results

a) *Undisturbed Disk*

The total H I map (Figs. 1 and 2) shows a structure very much like the optical photograph, but as in most spirals the outer arms are relatively more conspicuous in H I than optically. Though variable in strength, these arms can be followed over large distances. Further the bright optical arms also contain much neutral hydrogen with a ringlike structure which does not seem to be connected with the outer spiral structure. Inside the ring there is no trace of spiral arms, but the hydrogen is concentrated into a barlike structure, which, rather than being the true bar of a barred spiral, probably is related to the anomalous arms.

The velocity field (Fig. 3) looks very normal except in the inner parts which are evidently disturbed. Using the velocity field outside 10 kpc and assuming pure circular rotation, new geometrical (projection) parameters were deduced. Errors due to departures from circular rotation, as would be expected due to the presence of density waves, which were not included in the analysis, probably do not influence the determined angles by more than a few degrees. An estimate was made of the systemic velocity. The derived parameters are listed in Table 2.

From the full resolution velocity field a rotation curve (Fig. 4) was calculated, assuming the geometrical parameters listed in Table 2. Every point in the velocity field, except in the regions of the anomalous arms, was used with appropriate weights to compensate for differences in projection angle and uncertainties in the measured velocities as estimated from the local H I surface density.

In order to obtain a smoother rotation curve a mass model was fitted consisting of spherical core, a spherical halo and a flat disk, with density distributions of the following form:

$$\varrho_c = \varrho_{c,0} \cdot \exp\{-(R/R_c)^2\}$$
$$\varrho_h = \varrho_{h,0}/\{1+(R/R_h)^2\}$$
$$\sigma_d = \sigma_{d,0}/\{1+(R/R_d)^2\} .$$

The force contribution due to each of these components was derived by numerical integration.

A force law was calculated from the measured rotation curve, together with the appropriate weights. Various R_c, R_h and R_d's were tried until a reasonable fit to this force law could be attained by adjusting the densities. The derived parameters are listed in Table 3. It is stressed that this mass model was adopted with the aim of providing an interpolation formula for the smoothed rotation curve which did not imply an implausible mass distribution. The values of the individual parameters are of little physical significance. Only the total mass of the galaxy, which is still to some extent dependent on the distribution of mass between the disk and halo component, can be determined from the rotation curve.

Van der Kruit (1974) has measured Hα velocities in NGC 4258. Although we have not yet made a detailed comparison with our velocity distribution there seems to be a reasonable agreement between his and our data. The rotation curves as calculated by us and by Van der Kruit however are very different, ours being

Table 2. Geometrical and dynamical parameters of NGC 4258

Position angle of the line of nodes	$-28° \pm 2°$ (ascending node)
Inclination	$72° \pm 2°$
Systemic velocity	455 ± 8 km/s
H I mass	$4.5 \times 10^9 M_\odot$
Estimated total mass[a])	$(2.3 \pm 0.5) \times 10^{11} M_\odot$

[a]) The quoted error is an estimate of the range in mass possible assuming different distributions.

Table 3. Parameters of the mass model

Component	Density	Scale factor (kpc)	Masses out to 30 kpc ($10^{10} M_\odot$)
Core	$\varrho_{c,0} = 1.5 M_\odot \cdot \mathrm{pc}^{-3}$	$R_c = 1.4$	$M_c = 2.36$
Halo	$\varrho_{h,0} = 0.012 M_\odot \cdot \mathrm{pc}^{-3}$	$R_h = 1.8$	$M_h = 1.28$
Disk	$\sigma_{d,0} = 246 M_\odot \cdot \mathrm{pc}^{-2}$	$R_d = 10.5$	$M_d = 19.5$

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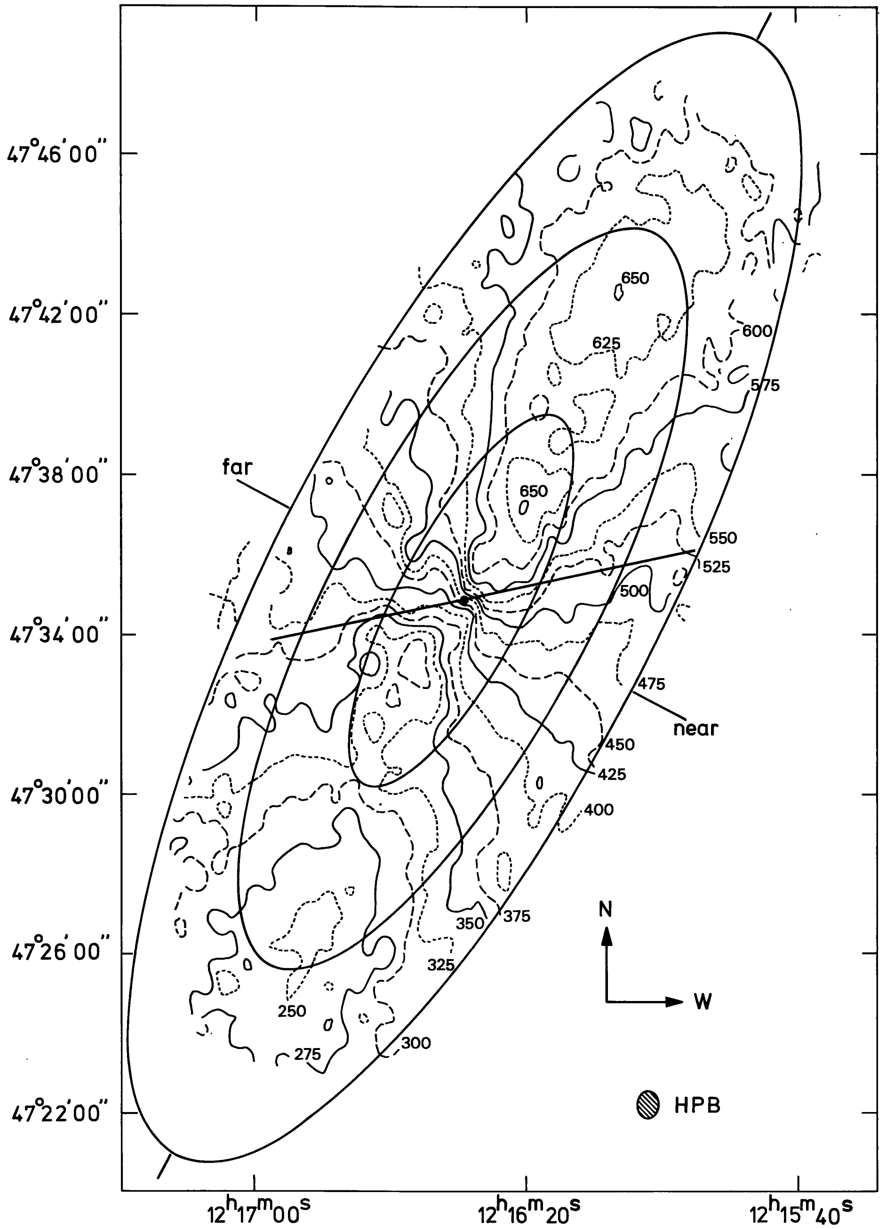

Fig. 3. Velocity field derived from single channel maps convolved to a half power beam width of 30″ × 41″. In the figure distances of 10, 20 and 30 kpc in the plane of the galaxy are indicated. The direction and length of the cross cut shown in Fig. 6 is drawn in (heavy line through the nucleus). The galaxy rotates counter clockwise. It proved to be impossible to construct a presentable looking velocity field at full resolution, though such a velocity field was used for the determination of the geometrical parameters and rotation curve. The velocity field shown here was determined by multiplying each intensity in each single channel map by a weight, zero for intensities below zero, rising to one for increasing intensities. The resultant maps were convolved to a 30″ × 41″ half power beam width and for each position an intensity weighted mean velocity was determined

much flatter and giving lower rotational velocities everywhere. This can probably be attributed to the difference in the assumed position angle for the line of nodes, to some difference in the choice of points used, and to the difference in resolution. Using a position angle of −28°, as assumed by us, instead of the −34° used by Van der Kruit will lower his rotation curve by an estimated 20%.

In order to gain insight into the deviations from circular rotation and to check the determined geometrical parameters, the systemic velocity and the rotation curve, a residual velocity field was calculated (Fig. 5). Some very large residuals are found, but these do not seem to be due to errors in the determined parameters. A slightly better overall fit should however be attainable with a somewhat smaller position angle and a slightly

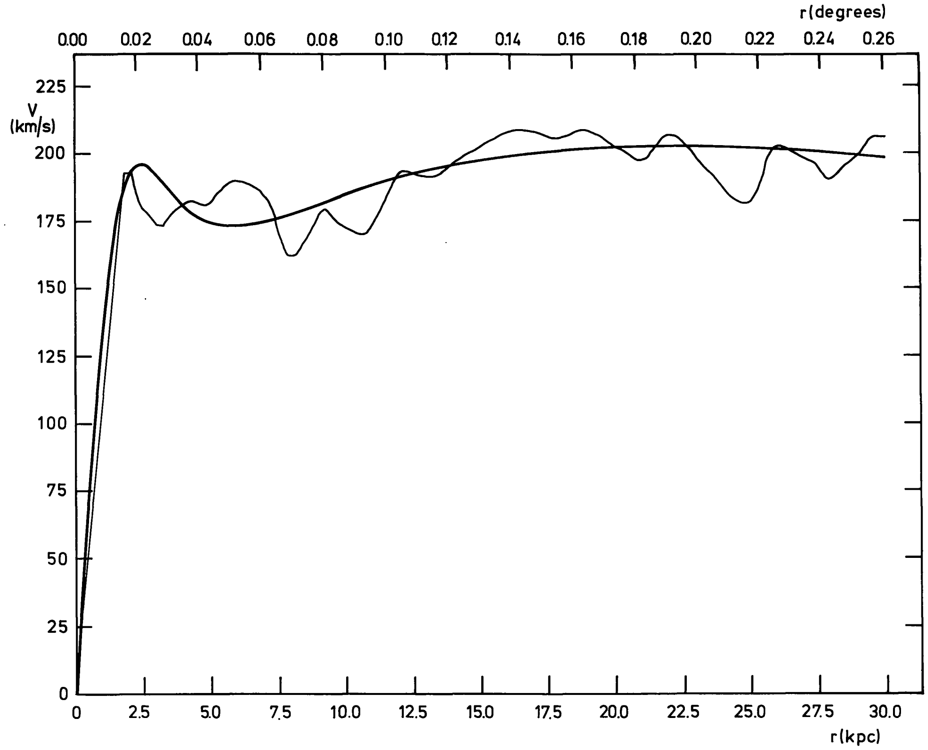

Fig. 4. Measured (thin) and smoothed (heavy) rotation curves. In the determination of the rotation curve no allowance was made for possible errors due to density wave streaming, which with a possible amplitude of 20 km/s may produce considerable distortions. As all points within 1.3 kpc of the center had to be rejected due to the presence of the anomalous arms, the rotation curve in this region was estimated by linear interpolation. The smoothed rotation curve corresponds to the mass model described in the text

lower systemic velocity. The large residuals in the anomalous arms are discussed below; those in the outermost region shown are due to noise. The smaller residuals in the remaining parts of the disk may be for a large part due to density waves. For the outermost western arm this could imply that it lies outside corotation because the denser gas in the arm moves outward relative to the interarm gas (see also Fig. 6).

Outside 10 kpc NGC 4258 seems to behave like a very normal spiral galaxy, while closer to the nucleus it is clearly disturbed.

b) The Anomalous Arms

From Figs. 1 and 2 it is evident that, in full agreement with the KOM model, the regions in and immediately in front of the anomalous arms contain very little H I in comparison with the rest of the disk.

Though not explicitly predicted, the H I bar seems to fit into the KOM model very well, but further calculations will be needed for confirmation. The following mechanism is proposed: in front of the anomalous arms the hydrogen has been swept up, and in the arms the hydrogen will still be ionized except at the front edge of the arms close to the nucleus, where the gas will have started to recombine. The resultant density contrast causes the appearance of the bar. The configuration of dust lanes and H II regions seen on optical photographs seems to confirm this picture.

Because of the relatively small amount of H I in the anomalous arms the velocities determined there will be less reliable than elsewhere. The large residual velocities evident in Fig. 5 certainly are significant but should not be regarded as a precise measurement. In accordance with the KOM model we find infalling motions in the anomalous arms (evident at position angles near 90°) and reduced rotational velocities (evident near the assumed line of nodes). No outflow is found. This is not surprising since any outflowing gas probably still is fully ionized, while it is also possible that the age of the anomalous arms is so high (they probably are much older than the 18 million years estimated by KOM) that all disturbed gas within 25 kpc has lost its outward motion. Most of the H I gas whose motion has been strongly disturbed by the expulsion is found within 10 kpc of the nucleus. Its mass is approximately $2 \times 10^8 M_\odot$. Since much of the disturbed gas will be ionized, the total mass involved may be several times larger.

As it cannot be judged from a map of mean velocities whether the line profiles in a galaxy show any anomalies (such as being double peaked), a number of cross cuts like the one in Fig. 6 were made. From the illustration it is evident that indeed information has been lost in the

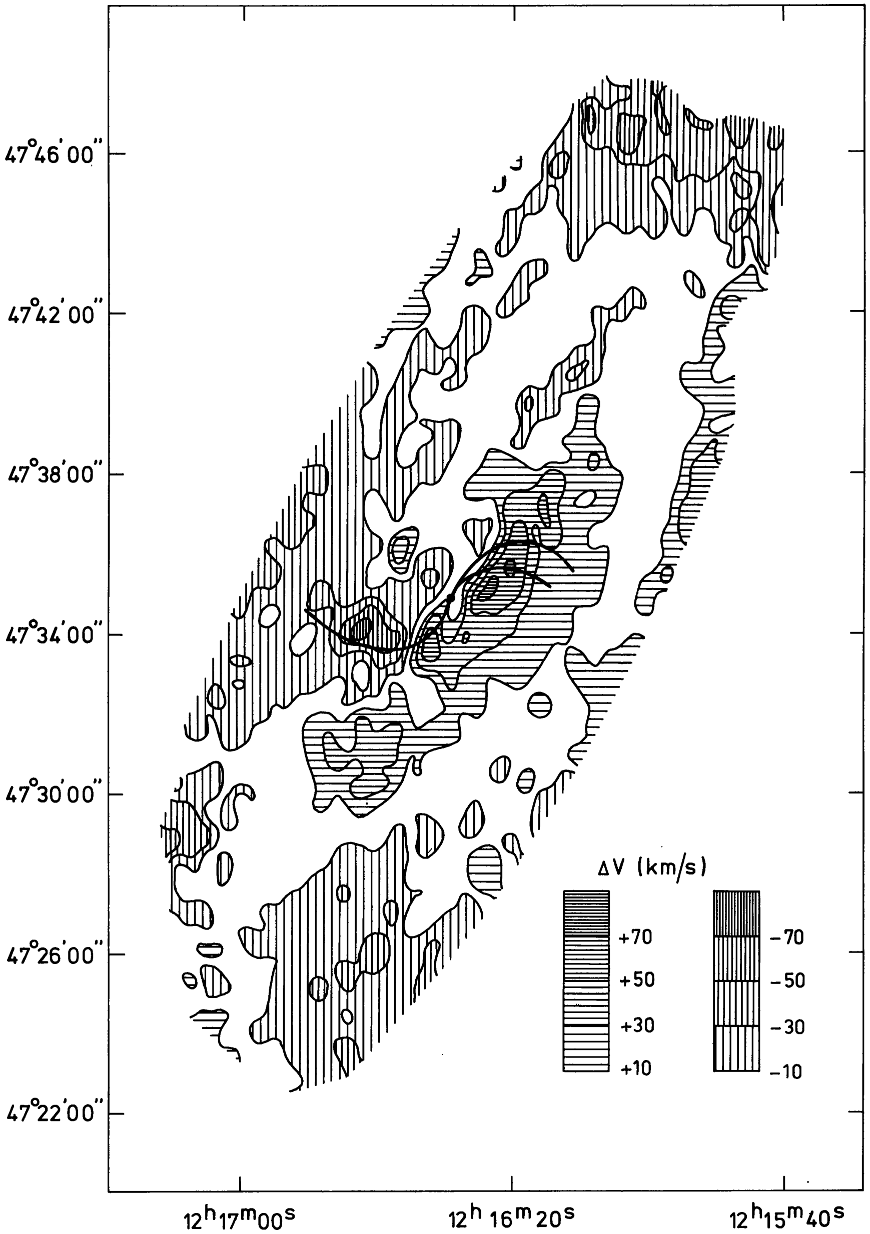

Fig. 5

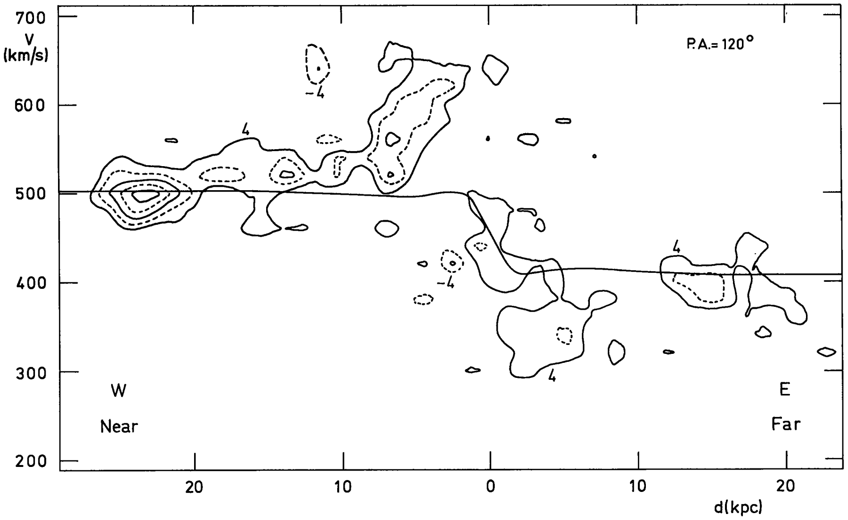

Fig. 6. Cross cut at position angle 102° through the nucleus. This figure shows the brightness temperatures in the various individual velocity channels along the line drawn in Fig. 3. The curve shows the velocities corresponding to the derived rotation curve of the galaxy. Contours at −8 K, +4 K, +12 K and +20 K are shown as solid curves, those at −4 K, +8 K and +16 K as broken curves. The 0 K contour is not plotted

Fig. 5. Residual velocity field. This residual velocity field was calculated by subtracting from the velocity field shown in Fig. 3 an artificial velocity field calculated from the smoothed rotation curve derived from the mass model as shown in Fig. 4. The artificial velocity field was corrected for beam smearing effects making use of the measured integrated brightness temperatures. The ridge line of the anomalous arms is indicated as in Fig. 1

construction of the velocity field. Neither the very high anomalous velocities at the western side near the nucleus nor of course, the double peaked profile at the eastern side can be deduced from Fig. 5. It is interesting to note that the hydrogen very close to the nucleus can be found in other cross cuts as well and seems to form a nuclear disk similar to that in our own Galaxy.

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References

Allen, R. J., Hamaker, J. P., Wellington, K. L. 1974, *Astron. & Astrophys.* **31**, 71
Baars, J. W. M., Hooghoudt, B. G. 1974, *Astron. & Astrophys.* **31**, 323
Burbidge, E. M., Burbidge, G. R., Prendergast, K. H. 1963, *Astrophys. J.* **138**, 375
Courtès, G., Cruvellier, P. 1961, *Compt. Rend. Acad. Sci. Paris* **253**, 218
Kruit, P. C. van der 1974, *Astrophys. J.* **192**, 1
Kruit, P. C. van der, Oort, J. H., Mathewson, D. S. 1972, *Astron. & Astrophys.* **21**, 169

G. D. van Albada
W. W. Shane
Sterrewacht, Huygens Laboratorium
Wassenaarseweg 78
Leiden-2405, The Netherlands

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