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IMAGING AND MODELLING THE DUSTY WINDS OF EVOLVED STARS

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ABSTRACT

Cm-wave MERLIN H_2O maser observations show that the outflows from early to mid-AGB stars are clumpy on a scale of 10-mas. DARWIN can be used as an imager the dust in these clumps. The MERLIN multi-epoch, high angular resolution observations (12-mas) of H_2O maser clouds show proper motions in the circumstellar envelope of the O-rich semi-regular variable RT Vir of 3-5 mas over a 10 week period. The proper motions of 18 maser clouds were measured with $> 2\sigma$ significance. At the Hipparcos distance of 140 pc these yielded a radial expansion velocity of 12 km/s and put a higher limit on any rotational component of < 0.2 km/s. These MERLIN observations measured the average cloud size to be 10 mas (1.4 au), and showed the density contrast between the clouds and the ambient medium to be 30:1. The Mid Infrared optical depth of the dust in these maser clouds would be between 0.1 and 1.0. The optical depth of the ambient material would be 30x less than this. Hence DARWIN can image MIR emission from these clouds, and the optical depth contrast is enough to separate the dust emission of the maser clouds from the ambient MIR emission. Therefore the high angular resolution MIR imaging capability of DARWIN would allow us to track dust clumps in stellar winds, and would show how and if radiation pressure on dust is the driver of mass loss from evolved stars.

Key words: DARWIN; dusty outflows; dust properties; clumpy winds.

1. INTRODUCTION

Mass-loss from long period variable red giants on the AGB phase of stellar evolution replenishes the ISM with nucleosynthesis products such as C,N,O and Si as molecules in gas and solid phase. It is by this process that efficient radiative coolant molecules and chemical surface catalysts are placed in the ISM. These products make for more efficient future star formation and hence greatly affects future evolution of the galactic ISM and stellar populations.

A typical AGB star of 1 $M_\odot$ radially pulsates with a period of 300 days. During the early and mid AGB the star loses mass at a rate of $10^{-6}\,M_\odot\,yr^{-1}$ for about 10^5 years. During this phase the star is optically visible, has warm IRAS colours and the 10μm Silicate feature is in emission. ISO observations of the dust continuum from these stars show the dust emission is from an optically thin media (when averaged over the arcminute ISO beam) from 10-200μm. However at the end of the AGB phase the mass-loss rate increases by 100 fold. The star becomes an OH-IR star and the envelope becomes optically thick at MIR wavelengths. By the end of the AGB the star will have lost up to 90% of its original mass. 99% of stars will then become a white dwarf star surrounded by a nebulae with both an ionised and molecular phase.

The role of dust is crucial in this mass-loss. Radiation pressure on dust is thought to drive the gas outflow via collisions (Chapman and Cohen 1986). Proper Motion studies of H_2O masers (Yates and Cohen 1994, Richards et al, 1996, 1998b, 1999) show that the gas is accelerated above the escape velocity in the region that ispopulated by water masers (3-30 AU). Simple kinematical models of radiation pressure on dust can reproduce the measured gas velocity fields; however the drift velocity between the gas and dust, and the change in dust properties with radial distance from the star are free parameters. Until they are constrained by measurements of the velocity field of the dust, and by imaging-spectroscopy of the dust emission, we cannot prove that radiation pressure on dust actually drives mass-loss from evolved stars.

In this paper we describe how 6-epoch 22-GHz MERLIN2 observations at milliarcsec resolution were used to measure the proper motions of circumstellar H_2O masers and hence determine velocity structure and density structure on scales of 2 mas (0.3 AU). These data show show the clumping scale of the mass loss wind to be 0.3-AU at 7-AU from the star. Finally we discuss how by combining of DARWIN observations

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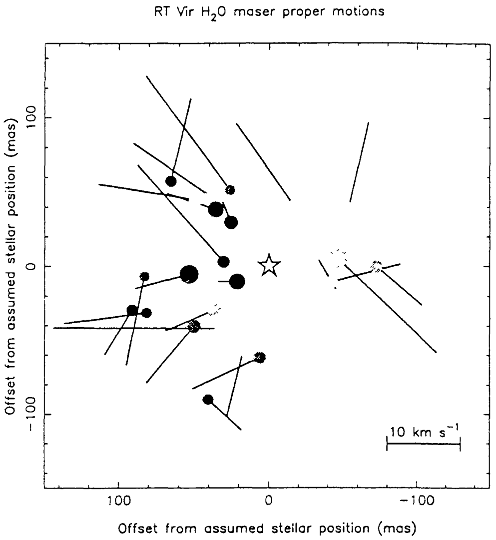

Figure 1. The H_2O maser proper motions at 6 epochs observed towards the semi-regular variable AGB star RT Vir over 10 weeks between April and June 1996. The proper motions are represented by heavy lines and are 10x their actual length. The maser features are represented by shaded circles; the darker the shading , the more red-shifted the maser cloud doppler velocity.

and accurate dust radiation transport techniques can show how the material in 99% of stellar atmospheres makes its way back in to the interstellar medium.

2. MEASURING THE VELOCITY FIELD AND CLOUD SIZES IN THE CIRCUMSTELLAR GAS USING 22-GHZ H_2O MASER MERLIN OBSERVATIONS

The semi-regular variable star RT Vir has a mass of $1.5 M_\odot$ and mass-loss rate of $3 \times 10^{-6}\,M_\odot\,yr^{-1}$. The Hipparcos distance is 140 pc. Yates and Cohen (1994) used MERLIN1 data (50-mas angular resolution) to show the 22-GHz H_2O maser emission was aligned E-W, with the blue-shifted emission offset to the W and the red-shifted emission offset to the East. The total velocity extent of the emission was 24 km s^{-1}, suggesting an expansion velocity of 12 km s^{-1} in the H_2O maser zone which had radial extent of 50-mas. Yates and Cohen suggested RT Vir was a strong candidate for a bipolar or rotating outflow.

2.1. Observations and Results

The 22-GHz H_2O maser emission towards RT Vir was observed at 6 epochs over 10 weeks from April to June 1996 by the UK MERLIN2. The beam size was 12 mas and the velocity resolution was 0.2 km s^{-1}. Typical rms sensitivity per channel was 30-mJy.

The MERLIN2 observations showed that the brightness distribution varied markedly over 10 weeks. The emission was spread over a region 140 mas (19 AU) in radius. The average inner radius of emission was 33 mas. 4.6 AU. The ability of MERLIN2 to detect structure on all spatial scales allowed us to measure the unbeamed sizes of the maser clouds. These turn out to be discrete dense clouds with a density contrast of 30:1 over the ambient medium, with sizes ranging from 2 to 16 mas. The typical cloud size is 10 mas. The clumpiness of the wind is clearly observed in Figure 2.

These clouds were used as proper motion markers to measure the velocity field in the inner 100 mas of the circumstellar envelope around RT Vir. 11 maser clouds were detected at all 6 epochs and a further 7 also had proper motions accurate to $> 2\sigma$. The proper motions and positions of the maser clouds are shown in Figure 1. The lines are a least-squares fit to the maser positions; however there is actually possibly some systematic curvature as well as scatter.

The average proper motion corresponds to an expansion velocity of 12 km s^{-1}, which agrees with that deduced from the maser spectrum. The proper motion velocities of the clouds are anticorrelated with their Doppler velocities, which is expected for an outflow. The proper motions show a strong radial expansion component and the expansion velocity is **not** dependent on position angle. However the brightest masers are found along a WNW-ESE axis. The tangential components are randomly directed and the extreme red- and blue-shifted maser clouds show detectable proper motions. The upper limit on the rotation velocity is 0.2 km s^{-1}, hence rotation is negligible 7-14 au from the star.

3. WHAT THIS MEANS FOR DARWIN OBSERVATIONS OF AGB STELLAR MASS-LOSS

3.1. Can we distinguish dust clumps from the general continuum ?

Maser physics suggests that H_2O masers clouds are pumped by collisional excitation of H_2O by H_2 followed by radiative de-excitation. This suggests that strong maser emission requires n_{H_2} to be $10^8 - 10^9\,cm^{-3}$. Using these densities with the measured cloud sizes for RT VIR of 10-mas, or 1.4AU, and a standard astronomical silicate model (Draine and Laor 1993) we predict cloud MIR dust optical depths of between 0.1 and 1. In addition the maser-dust clouds also will have cooler colours than the ambient material (**NB the ambient wind density is 30x lower**), because the higher cloud dust density will process more stellar continuum into MIR radiation. The combination of this increased MIR brightness and optical depth will allow the clumps to be seen against the dust emission in the ambient wind component.

The winds of early to mid-AGB stars therefore are

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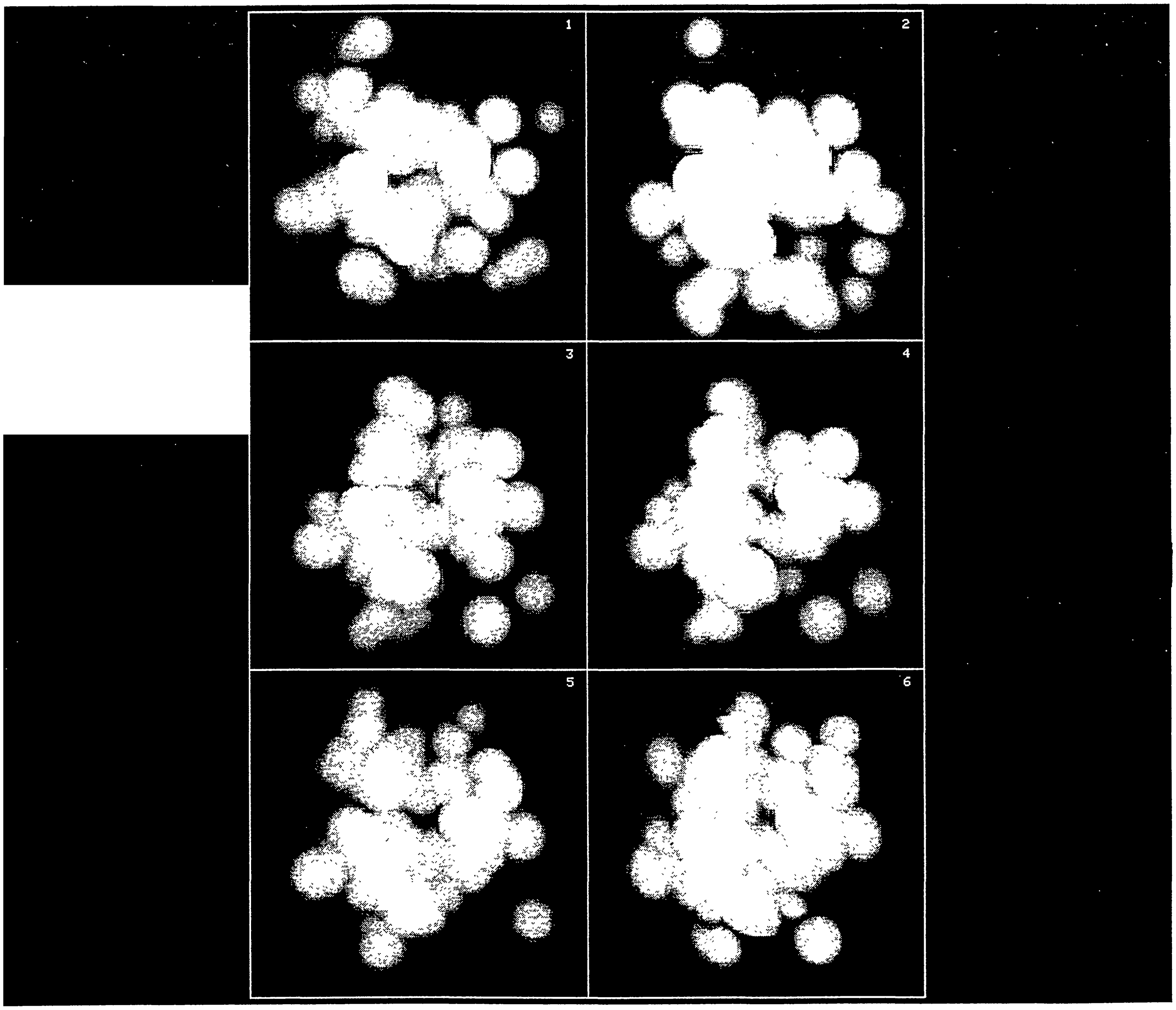
Figure 2. The H_2O maser cloud distribution at 6 epochs observed towards the semi-regular variable AGB star RT Vir over 10 weeks between April and June 1996. The cloud sizes are still convolved with the CLEAN beam of 12-mas. The deconvolved cloud sizes are between 2 and 16-mas, which corresponds to spatial diameters of 2.8 and 22.4 AU. The clouds show the inhomogeneous structure of the wind. Some clouds can be seen to move (by eye) between epochs. All clouds vary in brightness.



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optically thin. MERLIN maser observations suggest the winds are clumpy with the clumps having an enhanced density of 30:1 over the ambient. The higher MIR optical depths and cooler colours (higher MIR emissivity) of these clumps will make them readily identifiable by the DARWIN interferometer in its imaging mode.

3.2. An Experiment for DARWIN

DARWIN can measure the dust velocity field by proper motion experiments. DARWIN is designed to identify planets in the first case by measuring their orbital motion around the star. Therefore this experiment would fit neatly into DARWIN's mode of observing.

The proposed experiments will

1. Measure the proper motions of dust clouds at frequencies from 5-28μm.
2. Perform imaging-spectroscopy (if available) at R=50.

The wavelength range covers a range of dust temperatures (100-600 K). This will image the mass outflow at 1-6 mas angular resolution from 3-30 AU from the star. This will measure the proper motion of the dust clouds in the regions of strong radial acceleration to above escape velocity, to where the clouds are at constant radial velocity. These data need only be taken at 6 epochs over a 2-6 month time scale for each star we wish to observe.

The dust velocity field will show if the dust clouds are being driven by the stellar continuum. By comparing the dust velocity field to the gas velocity field we will measure the drift velocity between the gas and dust wind components; this would yield the degree of collisional momentum coupling between the gas and dust in the wind. These two measurements will show one way or the other if mass-loss from evolved stars is driven by stellar radiation pressure on dust grains.

Multi-colour observations, and possible imaging-spectroscopy, will be invaluable in determining (i) the composition, (ii) the size distribution and (iii) the crystallinity of dust particles **as a function of spatial position in the wind**. Richards et al 1998a presented strong high angular resolution gas kinematical evidence from observations of gas motions, which suggests that the properties which determine the optical constants of dust grains do change markedly with increasing radial distance from the star. Essentially the opacity increases with radial distance. Multi-colour imaging by DARWIN will show how dust grain properties evolve from their formation at 1-AU to their escape from stellar gravity at 30-AU.

3.3. Modelling DARWIN data : The Problems

Figure 3 demonstrates the current ability of modellers (in this case Efstathiou 1990) to use accurate 2-d dust radiation transport (RT) codes to deduce the temperature structure and dust density spatial distribution, including sin(i), from multi-colour dust observational data. However these models can only input homogeneous density and temperature structures, which our high resolution observations of H_2O maser observations show to be dangerous assumptions.

Therefore DARWIN will image very clumpy media. How do we model such media ? The effect of a clumpy media on a modelling strategy will be to force the modeller to use two wind components at the very least : the ambient and the clump. The ambient can be modelled as before, however clumps present the modeller with real difficulty. We will never know the exact starting conditions so we can never reproduce the observed clumpy brightness distribution. Even if we know the physics which produces the clumping we can only ever produce a simulated brightness distribution which **is similar. but not the same as the observations**. The existance of clumpy media also force all simulations to be 3-d and require the use of adaptive grid methods to ensure that radiation transport uniformily samples the optical depth structure of modelled object. Comparison methods do exist in other branches of Physics, which allow Monte-Carlo simulations to be compared with real data and an assessment be made of the success of the simulation. Modellers of DARWIN data will have to use such methods to get the maximum return from their modelling effort.

Not all is gloomy. High angular resolution multi-colour data can be modelled, even if we are forced to model the ambient and then independently model each clump. New dust radiation transport codes, new comparison methodologies and the DARWIN data will present theoreticians with the observational constraints they need to both predict how clumps form and how they evolve and interact with each other and the ambient wind component.

4. CONCLUSIONS

MERLIN cm-wave observations at 10-mas angular resolution show that the winds from early to mid-AGB stars are clumpy and that the dust in the clumps is of sufficient density and optical depth to be clearly imaged against the MIR continuum in these winds. DARWIN can therefore measure the proper motion of the dust components of these clumps and construct a dust velocity field. This will show (i) if the dust component is driven by stellar radiation pressure and (ii) if the dust component drives the gas wind. This will solve the long standing problem of how mass-loss from evolved stars is actually driven.

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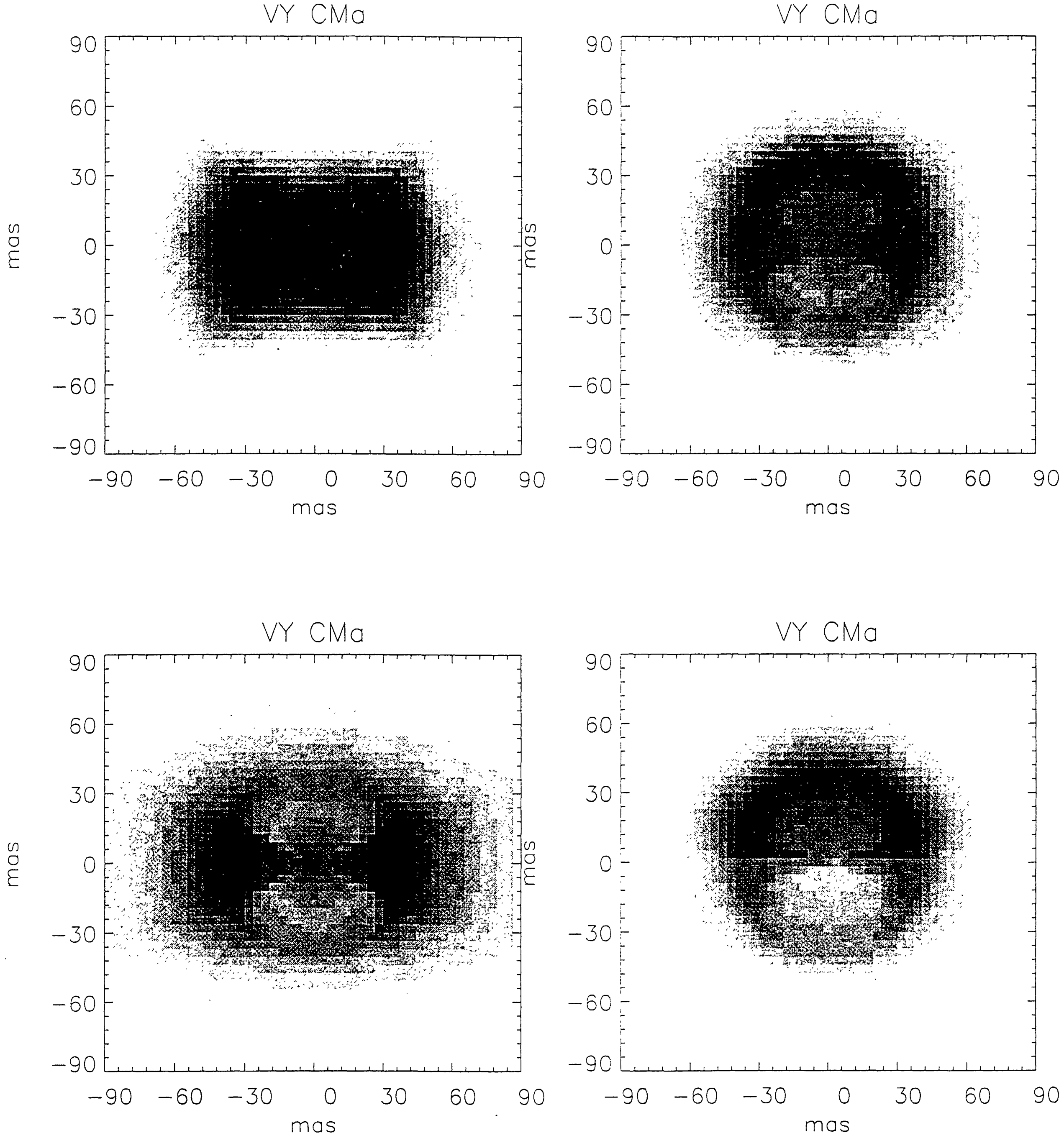
Figure 3. A 2-d dust RT simulations of the 5 (tlc), 10 (trc), 15 (brc) and 20 μm (blc) dust emission from the circumstellar envelope of the red supergiant VY CMA. The grain mix was for astronomical silicate and used 1 grain size (0.1 μm). The emission is mapped down to the same flux density level. As expected the overall size extent increases with wavelength, simply because emission from the colder dust (100-K) covers a greater spatial area. The input geometry was a thick disk model with an exponential reduction in density with increasing latitude above the disk. The trc and brc plots show the emission from the dust if the disk is inclined at 30 degrees to the line-of-sight; the tlc and blc plots are for a sky inclination angle of zero degrees. All the plots show the hotspots at the inner edge of the disk; this is where the dust is newly formed and at its highest thermal temperature. The input physical model used axial geometry and homogeneous distributions for the physical conditions.



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High angular resolution multi-colour observations of the dust emission from these winds has the potential to show how dust grains' composition and size distribution evolve from their formation to their escape from the star. However new 3-d radiation transport techniques and simulation methodologies have to be developed in order to properly model these DARWIN data.

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