SKA Studies of Atomic Gas in the Interstellar Medium of the Milky Way

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The λ21-cm line is an excellent tracer of the neutral interstellar medium. Atomic hydrogen (HI) is found in a variety of environments, from dense clouds to the diffuse galactic halo, and its filling factor is often high, so structures with sizes over a wide range of scales can be mapped with this line. Galactic HI surveys show small scale structure that is consistent with a spectrum of interstellar turbulence similar to what is measured in the ionized component of the interstellar medium. But our sampling of the spectrum of this turbulence is limited to a few size ranges, based on the sensitivities of existing telescopes for emission and absorption studies. The Square Kilometer Array will provide the sensitivity and resolution to give continuous coverage of the turbulence spectrum from hundreds of parsecs to a few tens of Astronomical Units. By showing us the full spectrum of interstellar turbulence in the neutral medium, the physical processes driving hydrodynamic and magneto-hydrodynamic instabilities will be illuminated. Ultimately the turbulence governs the passage of the gas from the warm phases of the medium to the cold phases where gravitational collapse can initiate star formation. The Square Kilometer Array is needed to fill in this missing link in the cycle of star formation and chemical enrichment that drives the evolution of galaxies. In the Milky Way halo, SKA mapping of HI high velocity clouds will trace the structure and motion of both the warm phase gas and the hot medium. The interaction between these two phases of halo gas is a great unsolved problem in Galactic astrophysics.

1. Introduction

Diffuse atomic gas in the interstellar medium (ISM) of the Milky Way and other galaxies can be most easily traced and studied using the λ21-cm line of neutral hydrogen (HI). The brightness temperature of this line is usually linearly proportional to the column density of gas, which makes it easy to interpret; coupled with the optical depth that is measurable in absorption toward continuum sources this line gives a good estimate of the kinetic temperature in the medium [8,16,7,13]. Best of all, hydrogen is the most abundant atom in the Galaxy, and the warm neutral medium is one of the most widespread phases of the ISM, so images made with the 21-cm line trace the largest structures (kiloparsec sizes) down to the smallest that can be resolved (hundreds of AU). The nature and origins of these structures in the Milky Way, and their related motions, define a fundamental astrophysical problem that the Square Kilometer Array (SKA) telescope will help to answer.

The gas disk of a spiral galaxy like the Milky Way is turbulent and inhomogeneous. On scales of a few kiloparsecs in size and a hundred million years in time, the spiral pattern in the stellar gravitational potential sweeps through the gas causing a shock, compression, and star formation [26,12]. On smaller scales of several hundred parsecs and ten million years, star formation and the concomitant stellar winds and supernova remnants shred the gas, sweeping out shells and bubbles and piling up clouds, often in the shape of sheets and filaments. These shells can break out of the disk and vent hot gas into the lower halo, driving a galactic fountain that redistributes gas radially. On still smaller scales of space and time the structure and motion of the gas is more random and irregular [3,15]. The kinetic energy injected by objects with sizes of tens of parsecs to kiloparsecs cascades to smaller scales by a turbulence process, the breakup of ordered velocity and density fields into random irregularities. Ultimately the energy is dissipated into microscopic motions on some smallest size or "inner scale". The dissipation scale is at least as small as 100 AU and may be as small as a few thousand kilometers. Between this and the outer scale, tens of parsecs or larger, on which the energy is injected, the structure of the interstellar medium in density and velocity is best described by a stochastic process with a power spectrum or structure function. These functions that describe the turbulence cascade of energy reflect the astrophysical processes that govern the dynamics of the gas. In particular, the motion of the gas is probably coupled to the magnetic field in a spectrum of magneto-acoustic waves [22,11].

Our knowledge of the structure function of the ISM is currently limited to a few narrow windows. These correspond to particular scales on which the turbulence influences the propagation of radiation from background sources. For the ionized gas, useful tracers of the structure on various scales are given by pulsar diffractive and refractive scintillation and dispersion measure changes (figure 1) [23,4,1]. For the cool neutral medium the optical depth can be mapped over the solid angle of extended background sources of high brightness, particularly compact double radio galaxies[9]. Using these techniques with existing telescopes gives measurements of the turbulence spectrum on a few particular length scales. Between these windows there are broad gaps of several orders of magnitude in size for which there are no tracers of the structure in the medium. Interpolating over these gaps using a power law structure function gives a rough description of the turbulence, generally supporting a Kolmogoroff type of energy conserving cascade. But the gaps between the measurements are wide, and a single power law is not a perfect fit even to the sparse data available today. The SKA will completely change this picture.

The square kilometer array will extend the range of sizes on which the structure in the density and velocity of the gas can be measured. The goal is to extend them so that they overlap, providing continuous measurements of the structure function over many orders of magnitude in scale. Using various observational techniques to trace the density and velocity fields of the neutral and ionized gas, the SKA will give a complete picture of the dynamics of the interstellar medium. Three example projects are described below and illustrated on figure 2.

2. Small scale 21-cm emission mapping - The Turbulence Cascade

The first project is modelled on the study of the spatial power spectrum of the 21-cm emission in the Southern Galactic Plane Survey (SGPS) [6]. The objective is to map the structure in the 21-cm line emission spectra over a randomly chosen area of one square degree at low Galactic latitudes. A deep integration of 500 hours on a single SKA field (one square degree) would give a very low noise spectral line cube that could be transformed to obtain the spatial power spectrum of the emission with unprecedented sensitivity. For beam size $\sim 5''$ (baselines ≤ 10 km) the rms noise would be 0.1 K in brightness temperature for velocity resolution of 1 km s^{-1}. Compared with the SGPS study, this sensitivity is a factor of ten better, and the resolution is a factor of 20 finer. Both improvements are needed together, as the amplitude of the spatial fluctuations is smaller when viewed on smaller and smaller scales. It would be possible with the same data, including baselines to 20 km, to make a cube with beam size $\sim 2.5''$ and rms noise 0.4 K. This approach would be excellent for studying specific structures having high brightness contrast, but the spatial power spectrum study presumes a typical, featureless region with no structure except the stochastic variations due to the turbulence itself. Resolution of $5''$ translates to linear sizes of 0.05 pc at a distance of 2 kpc, 0.25 pc at distance of 10 kpc. This is about the range of distances that can be distinguished accurately kinematically in a typical low latitude region. More nearby gas will dominate near zero velocity, but random motions make its

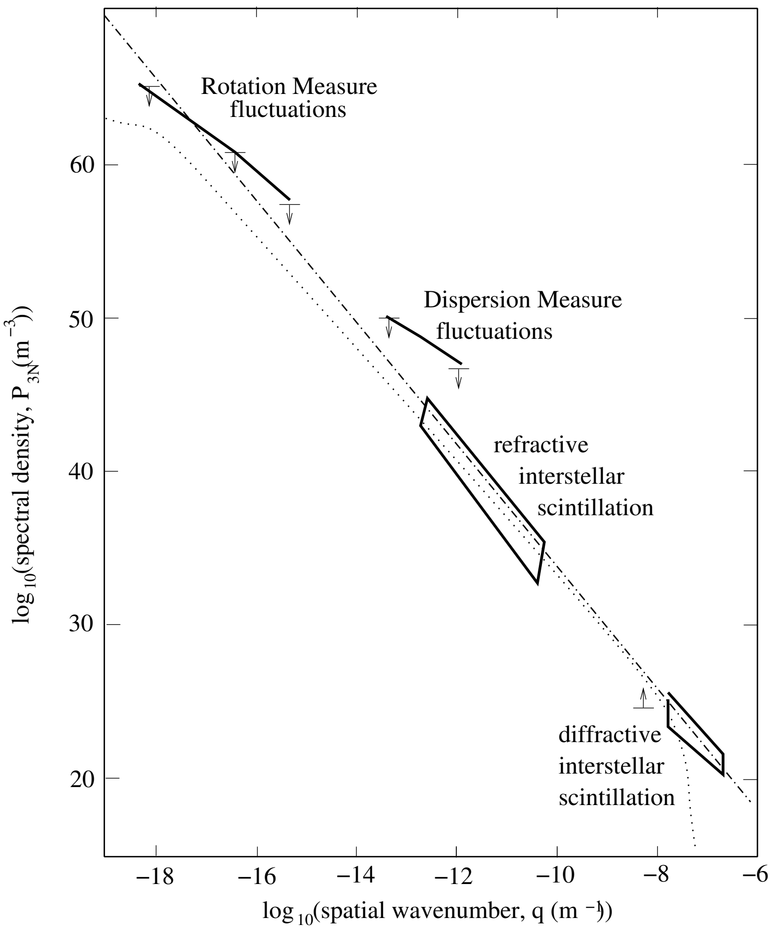

Figure 1. Turbulence in the ionized medium characterized by the structure function of density fluctuations (after [1]). The x-axis is the spatial wavenumber, the inverse of the linear size of the fluctuation, and the y-axis is the structure function, or three dimensional autocorrelation function of the density.

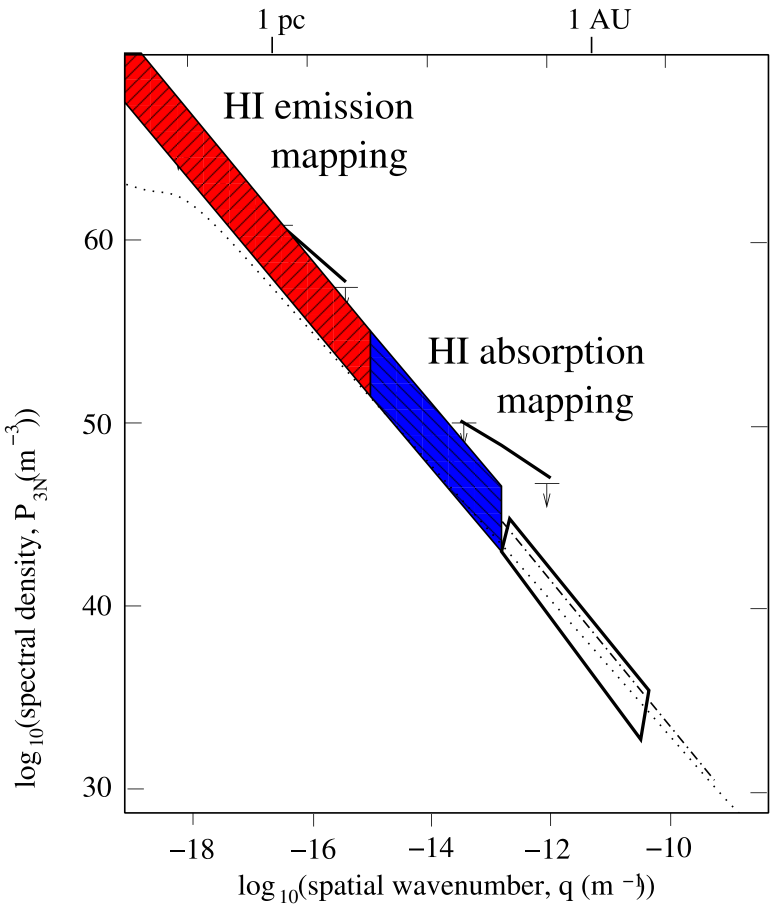

Figure 2. The range of spatial wavenumbers for turbulence in the neutral atomic medium that will be sampled by 21-cm mapping with the Square Kilometer Array. The axes are the same as in figure 1. The largest scales are the size of the Galactic disk overall, for both emission and absorption studies. The smallest scales are set by the brightness sensitivities in different hypothetical experiments described in sections 2 (emission) and 4 (absorption).

distance uncertain. On the larger scales, the one square degree field gives a maximum length scale 35 pc at 2 kpc distance, 175 pc at 10 kpc. Thus the result of this study will be a continuous measurement of the structure function over the range $\sim$ 200 to $\sim$0.05 pc (10^4 AU). On smaller scales the absorption project described below will continue this spectrum measurement down to scales of $\sim$ 10 AU with no gap between the observed size ranges.

3. Intermediate scale 21-cm emission mapping - Driving the Turbulence

On intermediate scales energy is injected into the ISM through stellar winds from massive stars and supernovae. In stellar clusters, where most of the massive stars reside, tens to hundreds of stellar winds and supernovae can inject energies in excess of $10^{52} - 10^{53}$ ergs into regions as small as 10 to 100 pc. These stellar winds and supernovae sweep up large shells of cool, neutral gas surrounding a hot, ionized interior. In external galaxies H I shells are a dominant source of structure, reshaping galaxies on size scales of tens to thousands of parsecs. H I shells can also grow large enough to exceed the scale height of the H I disk and break out into the halo creating a "chimney." Chimneys supply hot, metal-enriched gas to the Galactic halo and may act as a mechanism for spreading metals across the disk. H I shells play an important role in the evolution of the ISM by driving turbulence on scales of several hundred parsecs and also by providing a source of dissipation on small scales. For example, the dense swept-up walls of shells may be sites of cooling and molecular cloud formation, and from these clouds stars may form. We do not fully understand, however, how the gas makes the transition from the stellar outflow conditions (hot ionized medium) to cooler, neutral gas (warm neutral medium) and finally how it breaks up into cold, star forming clouds.

Recent high resolution images of large H I shells have allowed us to resolve, for the first time, a large fraction of this evolutionary life cycle of neutral gas in the ISM. Figure 3 is an image of a very large H I chimney, GSH 277+00+36 ([20,21]). GSH 277+00+36 is more than 600 pc in diameter and exhibits cold, parsec scale features along the walls of the shell. These features can be explained as Rayleigh-Taylor instabilities at the interface between the tenuous shell interior and the dense shell walls. These small-scale features are very cold, with gas temperatures as low as 40 - 50 K. Some even have associated molecular gas, as shown in contours on figure 3. Here we are able to observe the transition from the hot ionized medium presumably filling the interior of this shell, to the warm neutral medium of the outer walls, to the cold neutral medium in the smaller cloud condensations and finally molecular gas, all in one object.

Ultimately H I shells are destroyed by shear due to differential rotation in the Galaxy and by fragmentation as a result of instabilities in the shell walls. A variety of processes, including dynamical, Rayleigh-Taylor and gravitational instabilities, will slowly erode an H I shell, eventually rendering it indistinguishable from the turbulent ISM. In the process the size and distribution of the resulting structures provide fascinating probes of the physical conditions of the gas in the shell walls and interior. With sizes that can theoretically be as small as a fraction of a parsec, it is quite likely that we are only beginning to resolve these with the current generation of H I synthesis observations. The Square Kilometer Array will allow mapping of shells and chimneys similar to figure 3 everywhere in the Milky Way and Magellanic Clouds, and it will give us a complete inventory of shells of all sizes in spiral galaxy disks at least as far away as the Virgo Cluster ($\sim$15 Mpc).

4. 21-cm Absorption mapping - Dissipation

The small scale end of the turbulence cascade has been traced in the ionized medium by diffractive scintillation of pulsar radiation at low frequencies. This technique will extend to many more lines of sight, including all parts of the Galactic plane and the halo with the hugely expanded sample of pulsars that will be found with the SKA. The SKA will also allow measurements of the small scale variations in the density and

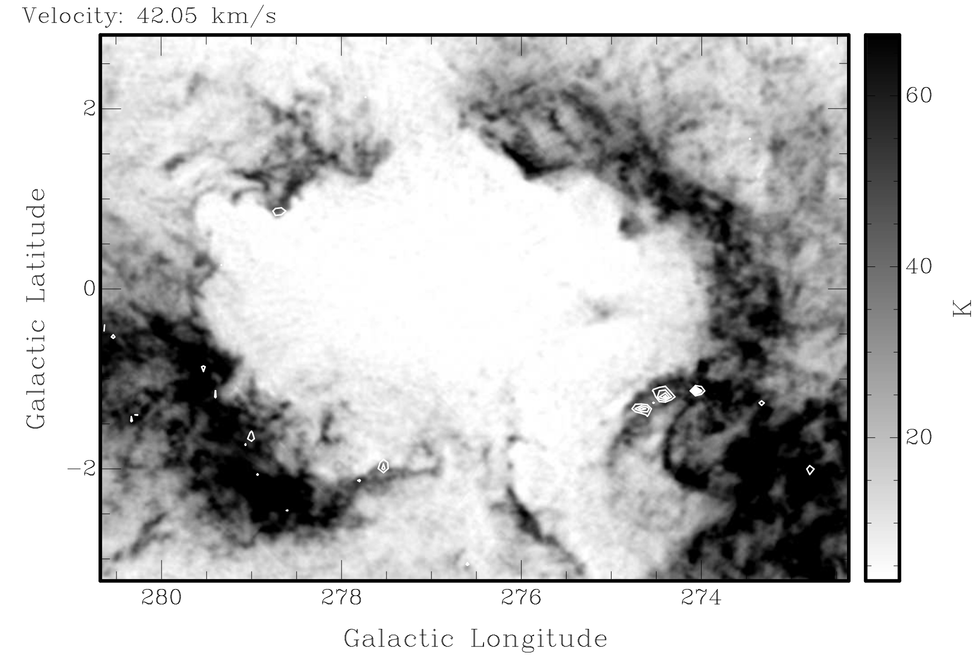

Figure 3. The H I chimney GSH 277+00+36 with the 21-cm brightness shown in grey scale, and contours showing the CO emission superposed. The "drips", or corrugations in the shell wall are instabilities that may represent the outer scale of the turbulence in the neutral medium [21].

velocity field of the neutral interstellar gas. This will be possible because of the vast improvement in the SKA over existing telescopes for measuring 21-cm absorption spectra.

By surveying absorption toward millions of continuum background sources with typical separations of three arc minutes on the sky, the SKA will show the variation of the 21-cm optical depth on scales of kiloparsecs down to a few tenths of a parsec. On smaller scales, mapping the absorption toward extended continuum sources like supernova remnants will allow variations in the 21-cm optical depth to be measured on angular scales of arc seconds [5]. Using VLBI techniques this can be extended to study of the structure in τ on angles as small as a few milli-arc second. This corresponds to a length of a few AU at a distance of 1 kpc. There is some observational evidence that this corresponds to the inner scale of the turbulence in the neutral medium [10]. The range of angular sizes that can be sampled using absorption techniques is indicated on figure 1 by the shading.

Measuring large numbers of 21-cm absorption spectra as part of a survey of the Galactic H I line is a project that uses the full advantage of the large field of view and high sensitivity of the SKA. With integration time of ten minutes per field we will achieve rms noise in absorption, σ_τ = 0.025 for continuum sources brighter than 10 mJy with spectral resolution of 1 km s^{-1}. There are roughly thirty sources per square degree at this level. A survey of 1000 square degrees (the Galactic plane with $|b| \leq 2.4^o$) will take about 170 hours, giving 30,000 absorption spectra with average spacing between sources of 15 arc minutes. Many of these background sources will be somewhat extended, and the absorption can be mapped over the solid angle of the continuum. These will extend the sampling of the structure function to a few milli-arc seconds, assuming that some very long baselines are included in the observation.

Going deeper, an integration of ten hours on a moderately bright supernova remnant will give a matrix of absorption spectra with high sensitivity for **spatial variations** in the optical depth. Even though the interferometer resolves out most of the continuum flux, in the spectral line all the continuum flux contributes to the sensitivity to small scale structure in optical depth. Thus a hypothetical remnant with flat surface brightness and total continuum flux density of 100 Jy spread over one square arc minute has flux of about 30 mJy per square arc second. A ten hour integration with spectral resolution of 1 km s^{-1} gives optical depth noise $\sigma_\tau = 0.025$ toward 1.3 mJy continuum flux. This corresponds to an area of 0.05 square arc seconds, or a spacing of 0.2 arc seconds between independent spectra. Thus variations of a few percent in optical depth can be detected over angles of a few tenths of arc seconds. For a brighter supernova remnant like Cas A (2000 Jy at λ21-cm) this method would reach to spatial resolution in absorption of 50 milliarc seconds. Even smaller spacings down to 10 milliarcseconds are given by using compact doubles as background sources. For these only two spectra are measured, but there are many such background sources available so that statistics of the variation of the optical depth on these angular scales can be measured accurately.

The result of such small scale absorption mapping is to extend the measurement of the structure function of the neutral gas density and velocity fields to much smaller scales than the emission mapping can trace. At a distance of 1 kpc, an angle of 50 milliarc seconds subtends 50 AU. The turbulence spectrum of the cool neutral medium on these scales must be critical in setting up the inhomogeneities in dense clouds that lead to the formation of stars and planets. By tracing the turbulence down to these small scales in a variety of environments we will see the initial conditions for the formation of dense molecular cores that collapse to become stars of various masses. Thus the preconditions for the initial mass function will be clarified.

5. Neutral Clouds in the Milky Way Halo

Beyond the Galactic disk lies a population of HI clouds which have an anomalous velocity, and whose origin has remained uncertain ever since their discovery more than 40 years ago (figure 4). Some of these high-velocity clouds are likely bound to the Galaxy (though they do not share in normal galactic rotation), and may be fragments left over from its formation. Others may represent primitive gas much further away, collected in the potential wells of small clumps of dark matter in the Milky Way's outer halo. Still others may be part of a genuine intergalactic population of "failed" galaxies which have not yet initiated significant star formation [19].

One difficulty in the study of these clouds is that the Doppler shift of the 21cm line gives only their radial velocity, not information on their full motion through space. However, if one can obtain a high angular resolution 21-cm map of a cloud with good sensitivity it is possible to estimate transverse velocity components by seeing the projected velocity change smoothly with position. This technique was used recently to determine the vertical motion of the high-velocity cloud Complex H [18], with the high resolution of the SKA it will be extended to many more.

The good resolution and sensitivity of the SKA will also allow us to examine the interface between the high-velocity clouds and the hot galactic halo with which some clouds are interacting. Gas at 10^6 K seems to pervade space around the Milky Way, but its true physical properties are highly uncertain [24,25]. It may contain a substantial percentage of the local baryons. High-velocity clouds can act as test particles as their motion through the hotter medium decelerates and rearranges the HI in a manner which depends on conditions in the surrounding medium [2,14]. Existing radio telescopes lack the angular resolution and sensitivity to study the interface zones between the warm (10^4) and hot (10^6 K) media. The SKA will provide maps of halo clouds down to column densities of $3{\times}10^{17}$ cm^{-2} over wide areas, to show the outer edges of the neutral medium.

It is quite likely that many spiral galaxies contain populations of halo clouds which are relics of their formation and products of their ongoing star formation. Study of these clouds in any but the closest systems is beyond the reach of existing telescopes, but it will be possible with the sensitivity and the resolution of the SKA. Knowledge of the properties of halo HI in galaxies of various types may provide a link between a galaxy's current morphology and the history of its formation.

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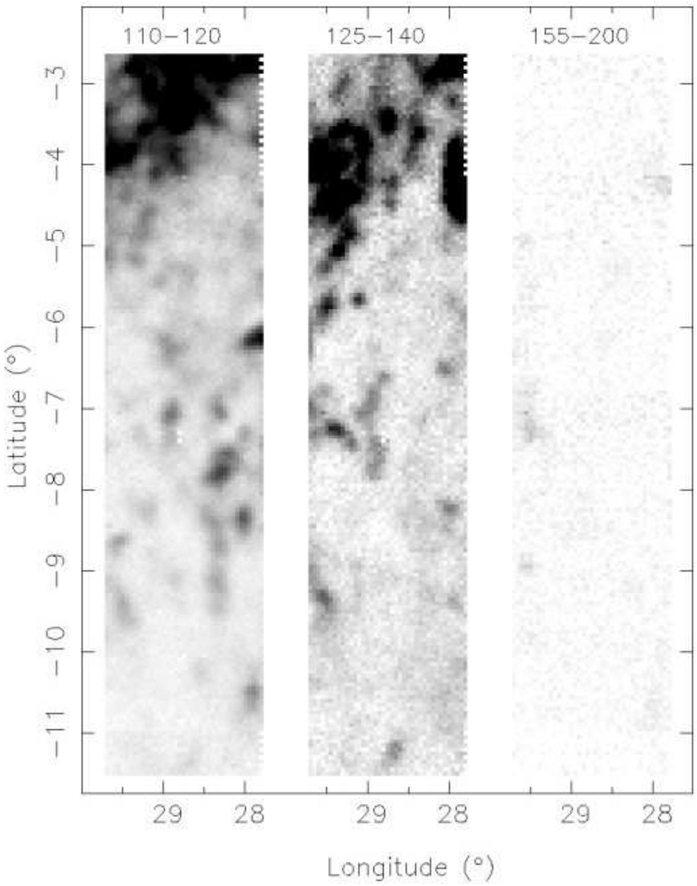

Figure 4. Neutral atomic clouds in the Milky Way Halo from [17]. The SKA will be able to trace clouds with sizes and masses two or more orders of magnitude smaller than these.

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