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The first detection of Far-Infrared emission associated with an extended HI disk[⋆]. The case of NGC 891

C. C. Popescu[1,2] and R. J. Tuffs[1]

[1] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany
e-mail: `Cristina.Popescu@mpi-hd.mpg.de; Richard.Tuffs@mpi-hd.mpg.de`
[2] Research Associate, The Astronomical Institute of the Romanian Academy, Bucharest, Romania

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Abstract. Spiral galaxies in the local universe are commonly observed to be embedded in extended disks of neutral hydrogen – the so called “extended HI disks”. Based on observations made using the ISOPHOT instrument on board the Infrared Space Observatory, we report the first detection of cold dust in the extended HI disk of a spiral galaxy. The detection was achieved through a dedicated deep Far-Infrared observation of a large field encompassing the entire HI disk of the edge-on spiral galaxy NGC 891. Our discovery indicates that the extended HI disk of NGC 891 is not primordial in origin.

Key words. galaxies: spiral – galaxies: structure – galaxies: evolution – ISM: dust – infrared: continuum

1. Introduction

Radial gas surface density profiles in spiral galaxies show quite similar behaviour in relation to the optical disk, irrespective of their morphological type (Sancisi 1995, 1999). Whereas the molecular gas is concentrated towards the inner disk, the HI surface density is generally flat at an average level of $10\,M_\odot\,\mathrm{pc}^{-2}$ over the entire extent of the optical disk (though with some variation from galaxy to galaxy, see Broeils & van Woerden 1994). Exterior to the optical disk, which tends to have a comparatively abrupt cut-off at ~3 stellar exponential scale lengths (Pohlen et al. 2000), the HI surface density falls off exponentially until a level of ca. $0.1\,M_\odot\,\mathrm{pc}^{-2}$ is reached. At this point the gas disk either ends, or becomes ionised by the intergalactic medium. The portion of the HI disk extending beyond the optical stellar disk is commonly referred to as the “extended HI disk”.

It is unknown whether these gaseous disks are remnants of primordial material left over from the epoch of galaxy formation (Larson 1990), or whether they contain material reprocessed in stellar interiors, either transferred from the stellar disk or captured from other galaxies. In the latter case the extended HI disks should be enriched by metals produced in stars (Tinsley & Larson 1978; Pei et al. 1999; Maller et al. 2001), so observations of these species could be used to identify their nature. Unfortunately metals in extended HI disks are difficult to detect in the gas phase, either through their emission line spectrum (because of the lack of exciting stars) or through absorption (because of the lack of sufficient background sources). However any metals present in form of dust grains offers an alternative way to trace the origin of these gaseous disks. Tentative evidence for the presence of metals in the form of grains was provided from measurements of colour variations between background galaxies and control fields (Zaritsky 1994). There is also evidence that, within the confines of the optical disk, grains have a larger scale length than the stars (Alton et al. 1998a; Davies et al. 1999; Trewhella et al. 2000; Radovich et al. 2001; Xilouris et al. 1998, 1999; Popescu et al. 2000a; Misiriotis et al. 2001) and that dust extends right up to the edge of the optical disks (Cuillandre et al. 2001). In some Blue Compact Dwarf galaxies observed in the FIR by Tuffs et al. (2002a,b) it has also been suggested that there is dust outside the optical emitting core region (Popescu et al. 2002).

Here we present the first detection of cold dust in an extended HI disk, achieved through a dedicated deep Far-Infrared (FIR) observation of a large field encompassing the entire HI disk of the edge-on spiral galaxy NGC 891, made using the ISOPHOT instrument (Lemke et al. 1996) on board the Infrared Space Observatory (ISO) (Kessler et al. 1996). We chose NGC 891 for this observation as it has an asymmetric HI disk (Swaters et al. 1997), so any FIR counterpart should also be asymmetric and thus be more easily recognisable.

2. Observations and data reduction

A detailed description of the observations and data reduction is given in Popescu et al. (2003). Here we give

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Send offprint requests to: C. C. Popescu,
e-mail: `Cristina.Popescu@mpi-hd.mpg.de`

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only a brief overview of these procedures. The observations were made using the ISOPHOT-C200 2×2 pixel array in the C160 and C200 filters, which respectively cover passbands of 130−218 and 170−239 μm and have central wavelengths of 170 and 200 μm. These FIR wavelengths were chosen since they provide maximum sensitivity to any cold dust present in the extended HI disk. Since there are no local heating sources in this region and the only available photons to heat the grains would be those coming from the optical disk, the FIR emission from any embedded dust was anticipated to be faint and have a spectral peak near our chosen filters. In order to cover the entire HI disk of NGC 891 (extending up to ~10 arcmin from the nucleus; Swaters et al. 1997), as well as the surrounding background, a field of radius ±13.5 arcmin (±40 kpc) was mapped along the major axis of the galaxy.

The FIR maps were obtained using the "P32" mapping mode which provided near Nyquist sampling over the three overlapping fields: north, south and central. Preliminary results obtained on the central field were presented by Popescu & Tuffs (2002a), Tuffs & Popescu (2003) and by Dupac et al. (2003). The data were processed using the latest P32 reduction package (Tuffs & Gabriel 2003), which corrects for the transient response of the detector pixels. This allowed high dynamic range maps to be constructed to levels of 1 percent of the peak disk brightness. A time dependent flat field correction was made for each map, by fitting a cubic function to the response of the detector pixels to the background. Calibration was made using V8.1 of the ISOPHOT Interactive Analysis Package PIA (Gabriel et al. 1997).

Radial profiles were derived from the background subtracted FIR maps by integrating the emission parallel to the minor axis of the galaxy in bins of width 18 arcsec along the major axis. Independent data contribute to each map pixel (and to each point on the profile) (Tuffs & Gabriel 2003).

3. Results

NGC 891 was found to be a normal galaxy in respect to its integrated FIR properties, such that the fraction of stellar light reradiated by dust in the FIR is ~30% (Popescu & Tuffs 2002a), which is close to the mean value for normal galaxies (Popescu & Tuffs 2002b). A detailed analysis of the FIR surface brightness distribution and profiles within the optical disk (±360″) has been presented in Popescu et al. (2003). There we find that the measured profiles and surface brightness distributions are in excellent agreement with the prediction for their counterparts obtained using the model for the optical/FIR/submm spectral energy distribution of Popescu et al. (2000a). The derived intrinsic distributions of dust and stars in NGC 891 were constrained from the optical/NIR images of NGC 891, as well as using data at 60, 100, 450 & 850 μm (Alton et al. 1998b) and data at 1.3 mm (Guelin et al. 1993). Here we compare the FIR profiles with the HI profiles and concentrate on the emission beyond the optical disk.

In Fig. 1 we show the resulting radial profile at 200 μm, overlaid with the corresponding HI profile. The latter was obtained from the HI maps of Swaters et al. (1997) after convolution to the PSF of the ISO measurements. Within ±200″ from the centre, where the HI radial profile is fairly flat, the 200 μm profile rises continuously towards the nucleus. This can be attributed in part to an increasing surface density of grains associated with molecular gas, which is known to predominate in the inner disk (García-Burillo & Guélin 1995), as well as to the stronger radiation fields from the inner parts of the galaxy. Between ±200″ and ±360″ (the edge of the optical disk) both the FIR and the HI profiles fall steeply. The 200 μm profile can be traced out to a radius of 522″ (24 kpc) in the South – 160″ (7.4 kpc) beyond the edge of the optical disk, and out to 432″ (19.9 kpc) in the North – 70″ beyond the optical disk. By comparison the HI profile extends out to 600″ in the South and out to 440″ in the North (Swaters et al. 1997). Thus, the extent and the asymmetry in the 200 μm emission follows that of the HI emission (the same is true for the 170 μm radial profile), indicating a dust emission counterpart to the extended HI disk.

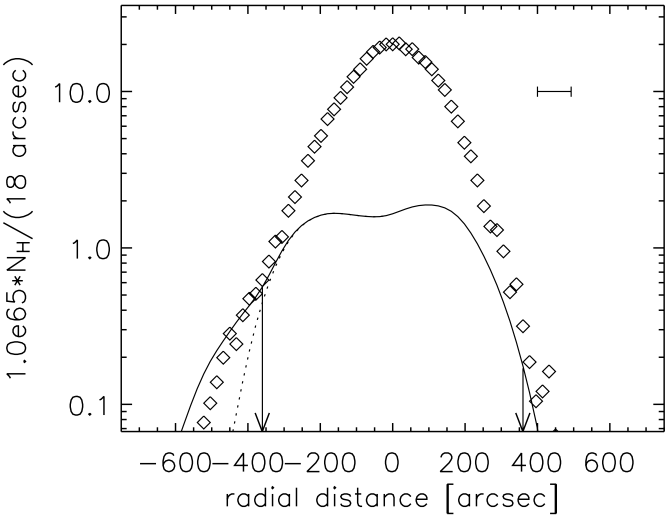

Fig. 1. The radial profiles of HI emission convolved with the ISOPHOT PSF (solid line) and of 200 μm FIR emission (symbols) sampled at intervals of 18 arcsec. The negative radii correspond to the southern side of the galaxy and the galaxy was scanned at 60 degrees with respect to the major axis. The units of the FIR profile are W/Hz/pixel, multiplied with a factor of 2×10^{-22} and the error bars are smaller than the symbols. The horizontal bar delineates the FWHM of the ISOPHOT PSF of 93″. The vertical arrows indicate the maximum extent of the optically emitting disk. The dotted line represents a modified HI profile obtained in the southern side from the original one by cutting off its emission at the edge of the optical disk and by convolving it with the ISOPHOT PSF.

In order to check that the FIR emission detected in the extended HI disk is not attributable to beam smearing of emission from within the outer confines of the optical disk, we truncated the HI distribution at the edge of the optical disk (such that no emission would exist beyond this edge), convolved it with the ISOPHOT beam, and overplotted the result in Fig. 1. It is clear that the FIR emission detected (in the South) beyond the optical disk falls above this modified HI profile, indicating that the detection is real and not of an instrumental nature. We also note that the bright emission from the central region of the galaxy would not contribute to the emission seen towards the extended

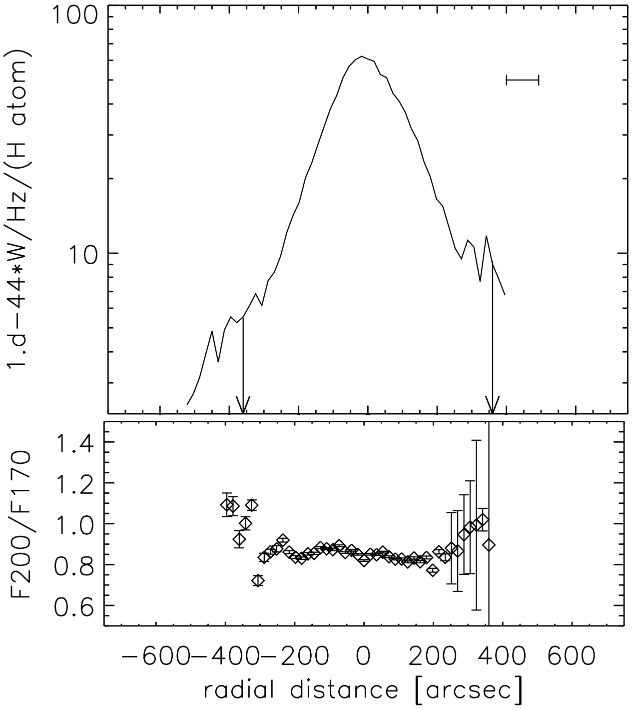

Fig. 2. Top panel: The radial profile of the ratio of the 200 μm and HI emission. Again the vertical arrows indicate the maximum extent of the optically emitting disk and the horizontal bar delineates the FWHM of the ISO PSF of 93″. Bottom panel: The radial colour profile F200/F170.

HI disk, as the ISOPHOT beam is known to fall steeply, and has no extended wings.

The relative rate at which the 200 μm and HI profiles decline with radius is best seen in Fig. 2 (top panel), where the profile of the ratio of these quantities is plotted. On the southern side this ratio decreases by a factor of 2.3 between 360″ (the edge of the optical disk) and 522″ (the maximum extent of the detected FIR emission). This could either be due to a decrease in the dust-to-gas ratio, or to a decrease in the grain heating with radius, or to a combination of the two. The dust-to-gas ratio can be calculated from the ratio plotted in Fig. 2 (top panel), if the dust temperature $T_{\rm D}$ is known. In Fig. 2 (bottom panel) it is shown that the 200/170 radial colour profile (measured as far as a radius of 400″) has a smooth progression towards colder emission with increasing radial distance, which can be taken as evidence that the dust at large galactic radii should be cold. From the 200/170 colour ratio of 1.1, as measured at a radius of 400″, and assuming a grain emissivity proportional to λ^{-2}, we derive $T_{\rm D} = 14\,{\rm K}$. This provides us with an upper limit for $T_{\rm D}$ at radii larger than 400″, because the radiation fields should decrease continuously with increasing distance from the edge of the optical disk. For the distance of NGC 891 of 9.5 Mpc (van der Kruit & Searle 1981) and assuming a mixture of silicate and graphite grains (Laor & Draine 1993; Draine & Lee 1984), we derive a dust-to-gas mass ratio of 0.0083 at the projected radius of 400″. This value is close to the dust-to-gas ratio of ~1% of both the local Galactic interstellar medium and of NGC 891 as a whole. Thus our measurements are consistent with there being little or no variation in the dust-to-gas ratio between the optical disk and the extended HI disk. So the radial fall-off in the ratio between the 200 μm and HI profiles in the extended HI disk is most probably due to the diminishing heating rate. This inference falls broadly in line with the expected decline in photon flux by a factor 2.1, if the photons heating the grains originate from near the edge of the optical disk.

4. Discussion and conclusions

The existence of large amounts of grains in the extended HI disk of NGC 891 raises the challenging question about their origin and the implications for the origin of the extended HI disk itself. The large value of the dust-to-gas ratio obtained for the extended HI disk clearly indicates that this gaseous disk is not primordial, left over from the epoch of galaxy formation. The detected grains must have either been transported from the optical disk, or they must have been produced outside the galaxy.

If the grains were transported from the optical disk continuously over the lifetime of the galaxy, only a very small fraction of grains produced in the optical disk need to be transferred to explain the derived dust mass in the extended HI disk, since there are no obvious grain destructions mechanisms operating there. Taking the lifetime of NGC 891 to be $\tau_{\rm gal} = 10^{10}\,{\rm yr}$ and the survival timescale of grains in the optical disk $\tau_{\rm surv} = 10^{8}\,{\rm yr}$, the total grain production mass is $M_D^{\rm tot} = (\tau_{\rm gal}/\tau_{\rm surv}) \times M_{\rm D}^{\rm opt}$, where $M_{\rm D}^{\rm opt}$ is the observed mass of grains in the optical disk at the current epoch (Popescu et al. 2000a). We obtain $M_D^{\rm tot} = 1.3 \times 10^{10}\,M_{\odot}$. If we compare this mass with the total mass of dust present in the extended HI disk $M_D^{\rm ext} = 2.3 \times 10^{6}\,M_{\odot}$ we can derive an efficiency of transfer of dust grains from the optical disk $\eta = 1.8 \times 10^{-4}$. Thus, it would only require a tiny amount of grains to be transported to the extended HI disk to account for the observations. This raises the possibility that the grains were transported via the prominent halo of NGC 891, as originally traced in Hα by Dettmar (1990) and Rand et al. (1990). For the specific case of transporting grains into the halo several mechanisms have been proposed by Ferrara (1991), Davies et al. (1998) and Popescu et al. (2000b), though no theory exists for the transport of grains through the halo to higher galactocentric radii. However it would be a remarkable coincidence that the transfer efficiency inferred from our observations should take exactly the value for which the present dust-to-gas ratio in the extended HI disk matches the dust-to-gas ratio in the optical disk. Furthermore any transport of grains via the halo should produce a symmetrical distribution of dust, contrary with what is observed.

An alternative mechanism for transporting grains and gas from the inner disk would be diffusion triggered by macro turbulence. To explain our observation, this mechanism would also have to be effective beyond the optical disk, in regions unperturbed by mechanical energy input from supernovae and stellar winds. A further requirement for this mechanism to be effective would be that the timescale for the mixing mechanism should be shorter than the timescale for grain destruction in the optical disk. As in the case of the transport of grains via the halo, an argument against this mechanism is however the observed asymmetry of the FIR profile.

Another possibility is that both the gas and the dust in the extended HI disk were part of the interstellar medium of another galaxy which was (long ago) tidally stripped and captured by NGC 891[1]. This would also explain the asymmetry in both the HI and in the dust. A present day example of such an interaction-accretion event is the advanced interaction of a dwarf galaxy with M 101 (van der Hulst & Sancisi 1988).

To conclude, while the exact mechanism through which the extended HI disk is formed remains unclear, our detection of FIR emission rules out a primordial origin of the extended HI disk in NGC 891. For the moment our result was obtained for one galaxy and cannot therefore be generalised to all spiral galaxies. However, future observations will be able to prove if in general extended HI disks of spiral galaxies contain large amounts of dust or if this is a characteristic peculiar to NGC 891. If the former is the case, then this implies that at the epoch when the first galaxies formed, there must have been a rather efficient process which removed primordial debris from around the forming galaxies, for example in a strong galactic wind, or simply as a result of a rather efficient conversion of gas into stars. Another implication of our detection of an asymmetric dust counterpart to the extended HI disk in NGC 891 is that the asymmetry of the latter is intrinsic rather than being due to the disk becoming ionised at a shorter radius.

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[1] We note that NGC 891 is thought to be a non-interacting system at the current epoch.