Search for Extra-planar Dust in Spiral Galaxies with Spitzer and AKARI*

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ABSTRACT

In this contribution we report on the detection of mid-infrared radiation extending to several kpc from the mid-planes of the nearby, edge-on galaxies NGC 891 and NGC 5907. The observations cover the range from 2 to more than 10 kpc on both sides of the disks. The detections were made with the peak-up imaging mode of the Infrared Spectrograph aboard *Spitzer* and the Infrared Camera (IRC) of AKARI. The surface brightness at 22 microns decreases exponentially with distance from the galaxies with scale heights of 1.3 $\pm$ 0.3 kpc (NGC 891) or 1.1 $\pm$ 0.3 kpc (NGC 5907). For NGC 891 we found the measured surface brightness profiles at 16 and 22 microns to be the same within the uncertainties of about 30%. The observed mid-infrared radiation is emitted by diffuse interstellar dust.

Both NGC 891 and NGC 5907 were mapped with *Spitzer* in a similar way, viz using one-dimensional rasters. NGC 5907 was also observed with the IRC. As the field of view of this instrument amounts to $10.3' \times 10.2'$, single pointings were here sufficient to obtain an image of the whole galaxy. We show that the extended emission, which was measured with *Spitzer* at only one position, is surrounding the whole galaxy, and that NGC 5907 appears at 24 μm largely undisturbed by its recently discovered neighbors.

Subject headings: galaxies: ISM — galaxies: individual (NGC 891, NGC 5907) — infrared: galaxies — infrared: ISM

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1. Introduction

NGC 891 and NGC 5907 are well-known spiral galaxies at distances of 9.8 Mpc (Tikhonov & Galazutdinova 2005) or 11.4 Mpc[†] (James & Casali 1998) respectively. At these distances $1''$ in an image corresponds to 48 and 55 pc perpendicular to the line of sight. They are particularly well-suited for the measurement of disk vertical structure.
Morphologically NGC 891 is a close twin to the Milky Way, with very similar (relative) sizes of bulge and disk - for a comparison of geometrical parameters see van der Kruit (1984). It is classified as being of type Sb and has an inclination of 89° (Dumke et al. 1997). Although it is a member of the NGC 1023 group of galaxies, it has no nearby massive companions and presents an undisturbed disk morphology. In these respects NGC 891 is not remarkable. It is unusual, however, on grounds of the large extension of its extra-planar Hα emission and a relatively high star formation rate.
NGC 5907 is of type Sc and seen under an inclination of 87° (James & Casali 1998). Unlike NGC 891 it shows no evidence for extra-planar, diffuse ionized gas, possibly because it is here more difficult to detect (Rand 1996). NGC 5907 has long been used as the prototype of a "non-interacting" warped galaxy, but this picture changed when Shang et al. (1998) found interactions with two companion dwarf galaxies.
The first investigations of the composition of disk galaxies in the mid-infrared were carried out with the aim to shed light on the nature of the "dark matter", whose gravitational influence causes the deviations from Keplerian motion in the rotation curves of galaxies. But searches with ISOCAM on board the Infrared Space Observatory (ISO) for a large population of brown dwarfs provided only upper limits of 1 MJy/sr for the halo (Gilmore & Unavane 1998). The frequency of observed micro-lensing events proved later conclusively that stars constitute only a small fraction of the mass of *our* Galaxy. Interstellar dust, however, can produce significant mid-infrared radiation, and the observations with *Spitzer* that we describe in the following were carried out with the aim to detect and characterize the diffuse extra-planar dust. The data obtained later with AKARI (Murakami et al. 2007) at similar wavelengths allow us to verify the results from *Spitzer* for NGC 5907 with images of the whole galaxy.

[†]15 Mpc if Virgo infall is taken into consideration (Mould et al. 2000).

2. Observations and Data Reduction

2.1. Spitzer

The observations were carried out with the Peak-Up Imaging (PUI) array of the Infrared Spectrometer (IRS) (Houck et al. 2004; Werner et al. 2004) as part of the guest observer program with the ID number P20016. Two collinear one-dimensional maps were obtained at either galaxy, each consisting of PUI pointings at $40''$ spacing (Fig. 1) and with dithering in case of NGC 5907. The one-dimensional maps were oriented orthogonal to the major axis of their galaxy.
The observations were planned in such a way to permit measurement and removal of known sources of error. The main potential problem in this respect arises from contamination of the signal by zodiacal light. The zodiacal light is significantly brighter than the targets outside the thin disks. Because its intensity varies by up to 2% on spatial scales comparable to the diameter of the galaxies, measurements at displaced reference positions do not provide a useful background measurement. Accordingly the maps themselves were used to characterize the zodiacal emission. We identified the galactic emission by using data points far away from the galactic plane for calculating linear fits to the brightness gradient of the zody.
The resulting surface brightness as a function of distance from the mid-plane of NGC 5907 is shown in Fig. 2. Globally the flux decreases with right ascension, a trend expected based on the model of the foreground emission in the *Spitzer* Planning Observation Tool. In addition there is a small but significant excess over the zodiacal light emission close to the galactic plane. For the analogous data from NGC 891 see Burgdorf et al. (2007).

2.2. AKARI

The observations were carried out with the AOT "IRC02" (Onaka et al. 2007) in the MIR channel as part of the Open-Time program "HALOS". They were scheduled for two different dates: 2006-12-29 and 2007-06-30 (24 μm). By comparing the data from different images it was possible to identify ghosts, latents, etc.
The raw data were processed with the imaging data reduction toolkit (Lorente et al. 2007). As the pipeline failed to co-add the MIRL images, we did this manually, i.e. not using the IRC TOOL. We eliminated negative outliers by ignoring their values when smoothing the image.

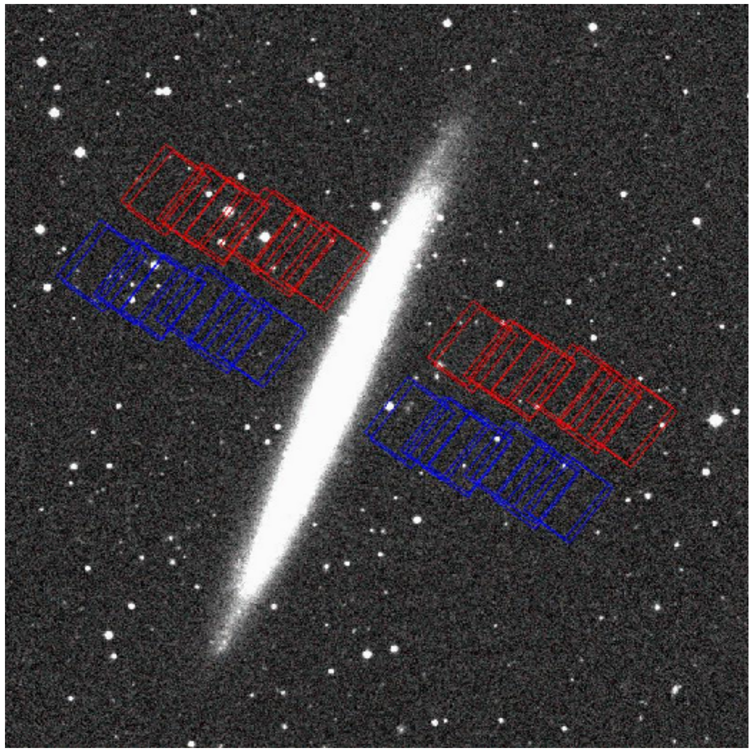

Fig. 1.— Position of the IRS-PU frames plotted over a POSS2 red DSS image of NGC 5907 (north up, east to the left; 15′×15′). Blue rectangles represent exposures in the blue IRS PUI band (not used in the following), while red rectangles correspond to the 18.5 - 26.0 μm regime.

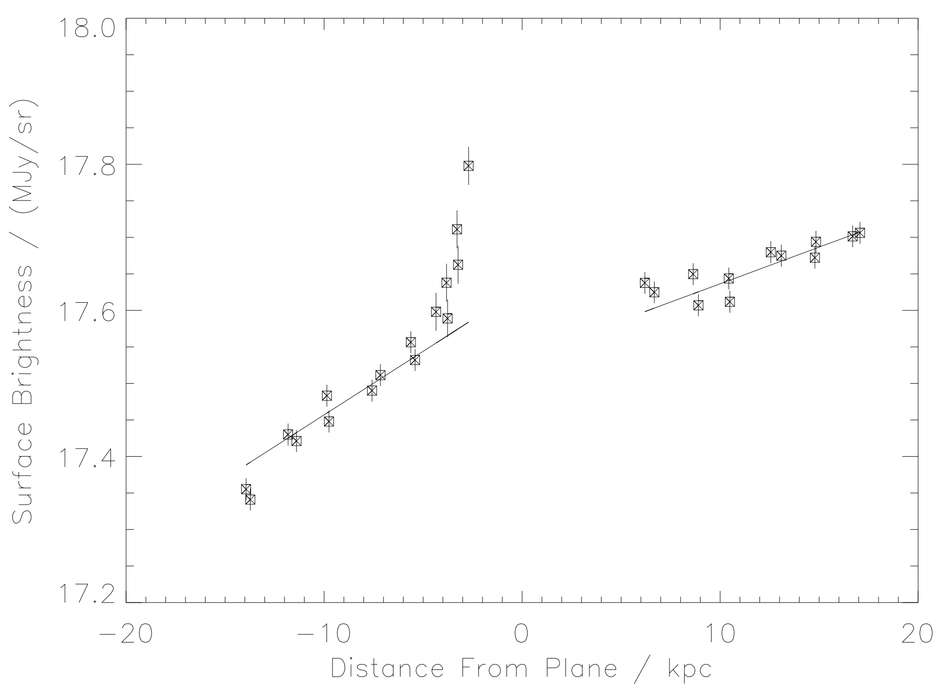

Fig. 2.— PUI signal of NGC 5907, averaged over the whole or a fraction of the peak-up array and scaled to the global model zodiacal values. Squares: PU red (22 μm). Solid lines: First order polynomials that fit best the points between 7 and 17 kpc from the disk.

3. Results

In order to isolate diffuse emission from NGC 891 and NGC 5907 in the data from *Spitzer*, we used separate linear functions on the two sides of the galaxies to fit and remove the foreground emission at large distances from the mid-plane, i.e. between 7 and 17 kpc, far from the disks. The uncertainties in the data were estimated from their scatter about the linear fit. Higher order terms in the spatial intensity distribution of the zodiacal light, if present, would therefore contribute noise to the measurements. We attribute the small mismatch between the extrapolated foreground emission from both sides of the galaxies to responsivity deviations below 1% between different Astronomical Observation Requests. This foreground removal has the side effect that any halo emission that might be present is subtracted as well. As the red maps from IRS-PU came only on the east side closer than 7 kpc to the galactic planes, the west area of the thick disks was not mapped at longer wavelengths. The result of this analysis for NGC 5907 is shown in Figure 3, with the foreground-subtracted flux density as a function of distance from the plane.
Beyond 50″ (corresponding to ≈ 2.5 kpc) the measured flux density follows for both galaxies an exponential decrease with distance from the plane. The scale height is 1.3 ± 0.3 kpc for NGC 891 (Burgdorf et al. 2007) and 1.1 ± 0.3 kpc for NGC 5907. The value for NGC 891 was also obtained independently on the basis of observations with the Multi-band Imaging Photometer (Kamphuis et al. 2007; Rieke et al. 2004).
It is here important to prove that there is only a negligible contribution from the relatively bright thin disk, via the wings of the IRS-PU point spread function, to the measured intensity profile at large distances from the plane. We estimated therefore its mid-infrared emission from the image with AKARI (see previous section). Multiplying the signal from each pixel along the thin disk with a normalized point spread function of *Spitzer* at the same wavelength, 24 μm, we derived its contribution to the extra-planar brightness. The result we got under the assumption that the vertical extension of the thin disk is smaller than 130 pc, i. e. a pixel of AKARI, is also shown in Fig. 3.

4. Summary

Our detection of flux at mid-infrared wavelengths around both galaxies confirms the presence of components with the geometrical shape of an exponential disk. In this connection it is worth mentioning that radio observations of HI in NGC 5907 disclosed the presence of a thick disk with a scale-height of 1.5 kpc (Dumke et al. 2000), i. e. somewhat higher than the value we found. Irwin & Madden (2006) claim the presence of an extended halo of Polycyclic Aromatic Hydrocarbons (PAH) emission with a characteristic scale height between 3.5 and 5 kpc, based on observations at 6.7 μm.

The surface brightness of the extra-planar emission of NGC 5907 in a distance of 4 kpc from the mid-plane is only about half that of NGC 891. This difference is not unexpected, given the fact that the dust mass in the "old dust disk" of NGC 891 is four times the amount of NGC 5907 and the star formation rate is 60 % higher in NGC 891 than in NGC 5907 (Misiriotis et al. 2001). Besides, there is more than double the amount of molecular hydrogen gas in NGC 891 as in NGC 5907 (Dumke et al. 1997).

Hence similar processes could be at work in both galaxies, viz the ejection of dust particles from the thin disk by galactic winds, and that the more as dust and wind is present. The big extent of the PAH halo in NGC 5907 might be due to sputtering of larger grains on their way away from the mid-plane. Such loss of atoms will happen to grains in a diffuse x-ray emitting halo like the one detected for NGC 891 (Strickland et al. 2004), but the importance of this process is certainly lower in the halo of NGC 5907.

Additional evidence for a scenario, in which stellar winds and supernovae efficiently expel dust into the intergalactic medium, comes from observations of the ultraviolet halos of edge-on galaxies with the *Galaxy Evolution Explorer*. Diffuse emission extends several kpc into the halo of NGC 253, and a substantial component of it could be ultraviolet light scattered by dust (Hoopes et al. 2005). We note in this connection also that de Jong et al. (2007) found a very flattened extension around the disk of the edge-on galaxy NGC 4244 in observations with the *Hubble Space Telescope* ACS. This halo formed presumably by a dynamical redistribution of mass, which heated the thin disk and spread the original stars into a thicker disk.

Two-dimensional maps with a field of view of $10.3' \times 10.2'$were obtained with AKARI. The one for 24 μm is shown in Fig. 4. On the basis of this map the presence of extended extra-planar emission is confirmed and shown to be symmetrically distributed with an elliptical shape around the thin disk. Any ring structure due to a nearby companion of NGC 5907 is not obvious in the image. A combination of this map with its counterparts at shorter wavelengths will be presented at a later date to characterize the distribution of PAHs and larger grains in two dimensions around the disk.

As mentioned above, we have subtracted any halo emission together with the gradient of the foreground emission from our data points from *Spitzer*. Such emission would explain why the total surface brightness as a function of right ascension changes even at large distances from both galaxies with different slopes on both sides, see Fig. 2 in this publication and in Burgdorf et al. (2007). If it exists, however, it must be fainter than 0.1 MJy/sterad, for it is hardly identifiable in the image from AKARI.

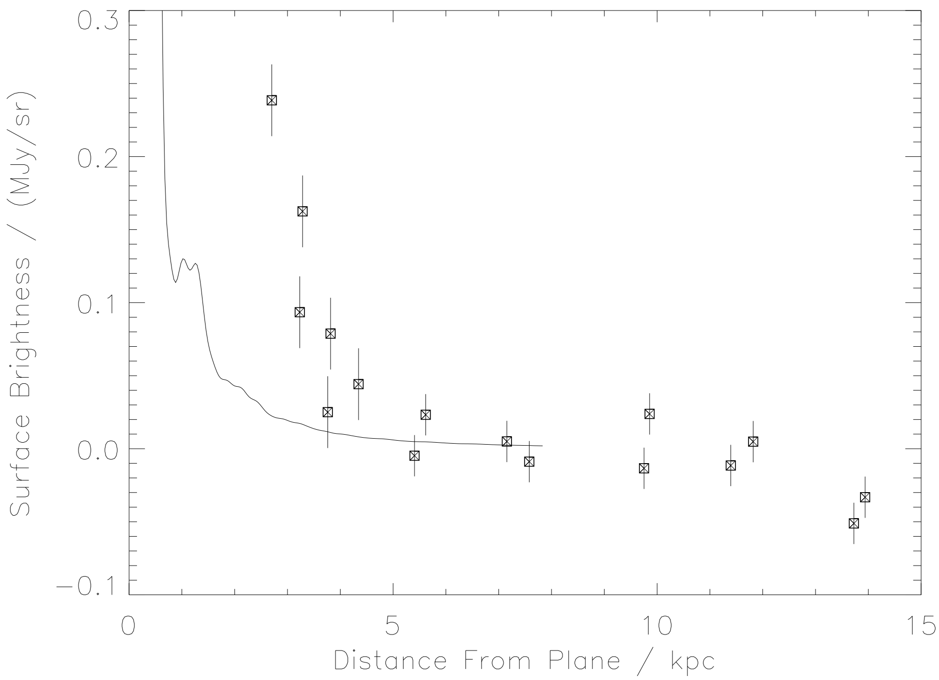

Fig. 3.— Average signal of NGC 5907 after subtraction of the foreground emission. Squares: IRS-PU red; solid line: intensity distribution expected from the thin disk only at 24 μm for the point spread function measured at the same wavelength with MIPS (no complete map of the galaxy is available at 22 μm).

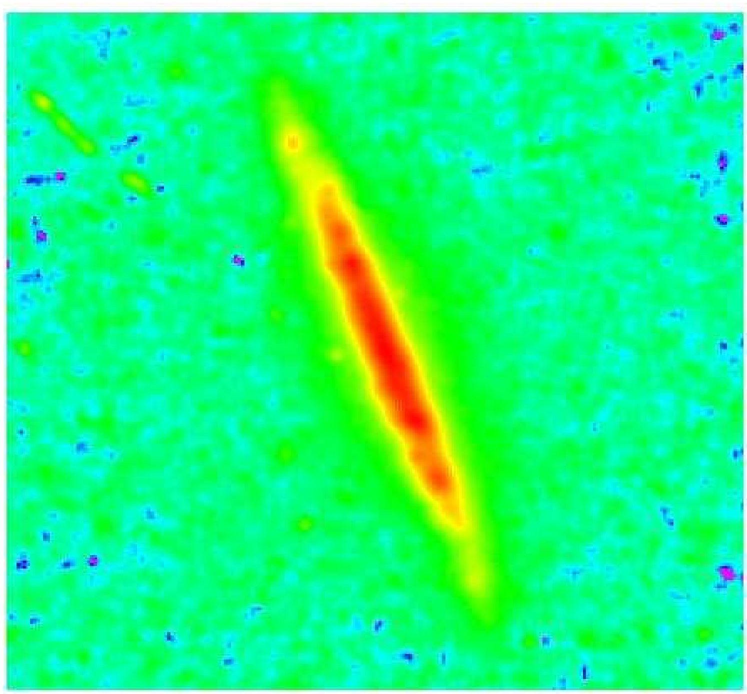

Fig. 4.— NGC 5907 at 24 μm (north 45° clockwise from right, east 45° from up), FoV = 10.3′ × 10.2′, logarithmic scaling, highest pixel value = 12 MJy/sr.

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