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# Star-forming complexes in the polar ring galaxy NGC660

**Abstract:** Galaxies with polar rings consist of two subsystems, a disk and a ring, which rotate almost in orthogonal planes. In this paper, we analyze the parameters characterizing the composition of the interstellar medium and star formation in star-forming complexes belonging to polar ring galaxy NGC660. We show that star-forming regions in the ring of the galaxy are distinctly different from those in the galaxy disk. They possess substantially lower infrared luminosities, which is indicative of less dust mass in these regions than in a typical disk star-forming region. UV and H$\alpha$ luminosities also appear to be lower in the ring, which is likely a consequence of its relatively recent formation.

**Keywords:** NGC660-galaxies: star formation

## 1 Introduction

The interstellar medium (ISM) is both a stage and a source of material for the star formation process. Its composition defines the rate and spatial distribution of star formation in a galaxy. In order to recover specific details of this process, we need to know the relative contribution of various ISM components (atomic gas, molecular gas, dust, radiation field, etc.). Rapid development of observational tools allows these components to be studied separately from each other. Interacting galaxies are especially interesting from this point of view, where there exists a certain perturbing factor triggering the appearance of new star-forming regions (SFRs). This leads to a rejuvenation of the stellar population of the galaxy and may clear up some features of the ISM evolution.

We are interested in such objects where we can observe young regions of star formation. Galaxies with polar rings are good candidates for this role. At the moment, about 400 polar ring galaxy candidates and confirmed polar ring galaxies are listed in two catalogs: Whitmore *et al.* (1990) and Moiseev *et al.* (2011).To perform a detailed analysis of observational tracers of various ISM components, we need a large set of observational data for each object,

covering as wide a wavelength range as possible. This condition is satisfied only in a few objects. For our research, we need an extended ring to isolate star-forming regions, belonging to it. We also need the ring to be well separated from the host galaxy so that we can analyze emission separately for the two subsystems. The galaxy should not be far away so that individual star-forming complexes can be resolved.

So far, there seems to be just one galaxy suitable for our purposes. This is galaxy NGC660, located at a distance of 13 Mpc (Tully *et al.* 2013) and included in the catalogue by Whitmore *et al.* (1990) under the number C-13. The galaxy NGC660 was confirmed to be a polar ring galaxy with a strongly inclined extended ring according to H I observations by Gottesman and Mahon (1990). In contrast with most other polar rings, which surround early-type gas-free galaxies, the central disk of NGC660 contains molecular and atomic gas as well as star forming regions. The study of gas kinematics provides evidence of direct interaction between matter in the external ring and inner disk (Moiseev 2014).

In Smirnova *et al.* (2017), we investigated relations between various components of the ISM in 11 galaxies included in a number of observational surveys, including THINGS (H I line observations at 21 cm using the Karl G. Jansky Very Large Array), KINGFISH (observations in the far infrared region at 70, 100, and 160 µm using the Herschel Space Observatory), SINGS (observations in the near-infrared and mid-infrared bands at 3.6, 4.5, 5.8, 8.0 and 24 µm using the Spitzer Space Telescope), and HERA-CLES (CO 2—1 line observations using the IRAM 30 m telescope). Infrared (IR) data were also used in Smirnova *et al.*

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(2017) to estimate the total dust mass ($M$), the fractional mass of polycyclic aromatic hydrocarbons ($q_{PAH}$), and the radiation field strength ($U$) using the model by Draine and Li (2007). In this study, we want to take advantage of the obtained patterns for these 'normal' galaxies and to compare them with the similar results for the galaxy NGC660. Data in the far IR range are not available for this galaxy, so we cannot use the Draine and Lee dust model. We can estimate the radiation field that heats up the dust, using data in the ultraviolet range and the H$\alpha$ line.

# 2 Data

In this section we present the available observational data for the galaxy NGC660, as well as their processing. We have identified star-forming complexes in the disk and the ring of the galaxy. In all the ranges we performed the aperture photometry of the same complexes. A typical size of an aperture is about $15''$ which, at the distance of NGC660, corresponds to slightly less that 1 kpc (the accepted scale is 63 pc/$''$). This is roughly compatible with the expected maximum SFR size (Elmegreen *et al.* 1996).
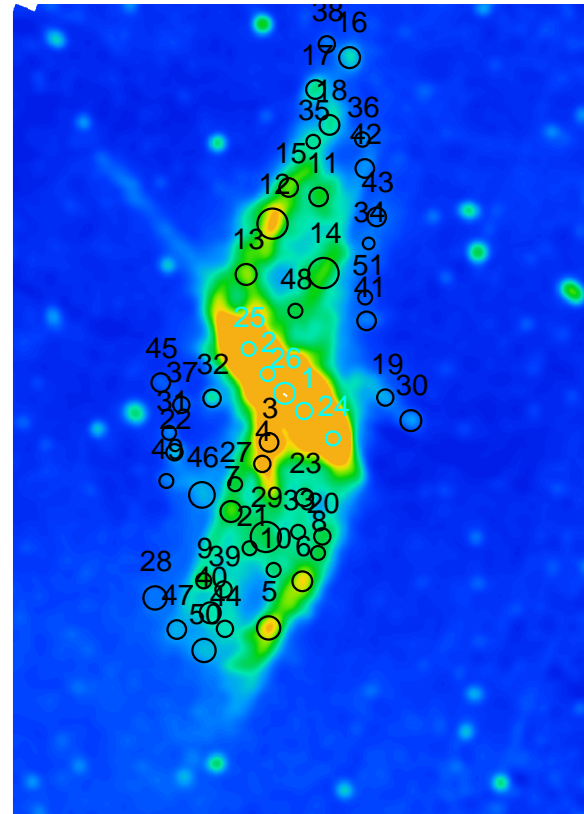
## 2.1 Observations

For the galaxy NGC660, we used archival data in the IR and ultraviolet (UV) ranges. Near-IR observations (wavelengths of 3.6, 4.5, 5.8 and 8.0 μm) are taken from the SINGS survey[1] performed with the Spitzer Space Telescope. The data in the mid-IR region (22 μm) were taken from the WISE archive[2] (Wright *et al.* 2010) and data in the UV range are extracted from the GALEX archive (Martin *et al.* 2005).

Observations in the H$\alpha$ emission line were performed with the 6-meter telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) using the scanning Fabry-Perot interferometer in the multi-mode SCORPIO focal reducer (Afanasiev and Moiseev 2013).

Since the point spread functions (PSFs) of different instruments and passbands differ from each other, we convolved near-IR, mid-IR and 21 cm images to the resolution of 22 μm WISE images, using the IDL convolution procedure and kernels provided by Aniano *et al.* (2011).

## 2.2 Aperture Photometry

Regions for aperture photometry in the NGC660 galaxy were selected both in the disk of the galaxy and in its ring (Figure 1). The ring of the galaxy has quite an extended structure, which allows selecting numerous star-forming complexes. The disk of the galaxy is seen almost edge-on. Thus, we have only been able to identify a few of the brightest regions there.



**Fig. 1.** An 8 μm image of NGC660 with overlayed star-forming regions. Regions 1, 2, 24, 25, 26 belong to the galaxy disk. Other regions are located in the ring.

After the regions were selected, the convolved images were used to perform aperture photometry. The aperture radius is chosen separately for each H II complex, depending on its angular size. The total flux was corrected for the contribution of partial pixels. Photometry procedure and error estimation are described in Khramtsova *et al.* (2013). Eventually, we obtain radiation fluxes in the near- and mid-IR bands as well as in the UV range and in H$\alpha$. A significant fraction of the emission at 8 and 22 μm is generated by stars. Emission at 8 μm is produced not only by polycyclic aromatic hydrocarbons (PAHs), but also by hot larger dust grains. In order to distinguish only the PAH
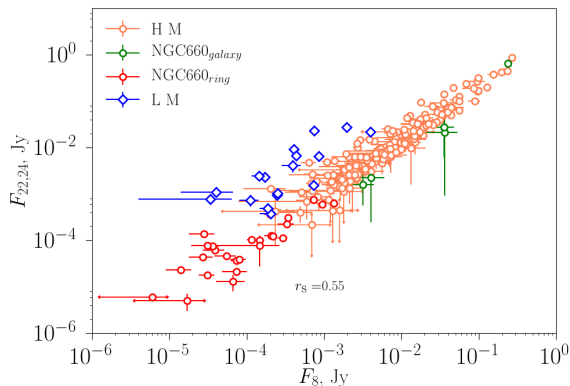
emission at 8 μm ($F_8^{\text{afe}}$) and only the very small grains (VSG) emission at 22 μm ($F_{22}^{\text{ns}}$), we applied the method for estimating the stellar and large grain contributions described in Marble *et al.* (2010).

# 3 Results

The main goal of our study is the relation of dust and gas properties in the regions of star formation. We assume that radiation in the near-IR (in particular, at 8 μm) is generated by small aromatic particles of PAH, while emission in the mid-IR (in particular, at 22 and 24 μm) is produced by larger hot dust grains. In both cases, to generate IR emission it is necessary to heat dust particles with UV radiation. Therefore, we assume that spots of intense near- and mid-IR radiation are SFRs.



**Fig. 2.** Comparison of fluxes from SFRs in NGC660 at 8 μm and 22 μm. For comparison, 8 and 24 μm fluxes are also shown for high and low metallicity extragalactic SFRs in 11 galaxies studied in Smirnova *et al.* (2017).

The general relation of fluxes at 8 and 22 μm is shown in Figure 2. Also in this graph we show fluxes at 8 and 24 μm from SFRs studied in Smirnova *et al.* (2017). Orange circles correspond to SFRs in galaxies of high metallicity. Blue diamonds show SFRs in galaxies of low metallicity. As noted in Smirnova *et al.* (2017), data points for low metallicity SFRs in this diagram are located slightly above the points for SFRs of high metallicity. This indicates a known dependence of flux ratio at 8 μm to 24 μm (or 22 μm) on metallicity (Engelbracht *et al.* 2005). Clearly, the SFRs from the NGC660 disk (green circles) are located in the same region of the diagram as the high-metallicity SFRs from the other star-forming galaxies (the sample from Smirnova *et al.* (2017) includes both spirals and irregulars). The SFRs

from the NGC660 ring (red circles) occupy a different position in the diagram. While demonstrating the same ratio of the two fluxes as the other SFRs of high metallicity, they are significantly dimmer both at 8 μm and at 22 μm.
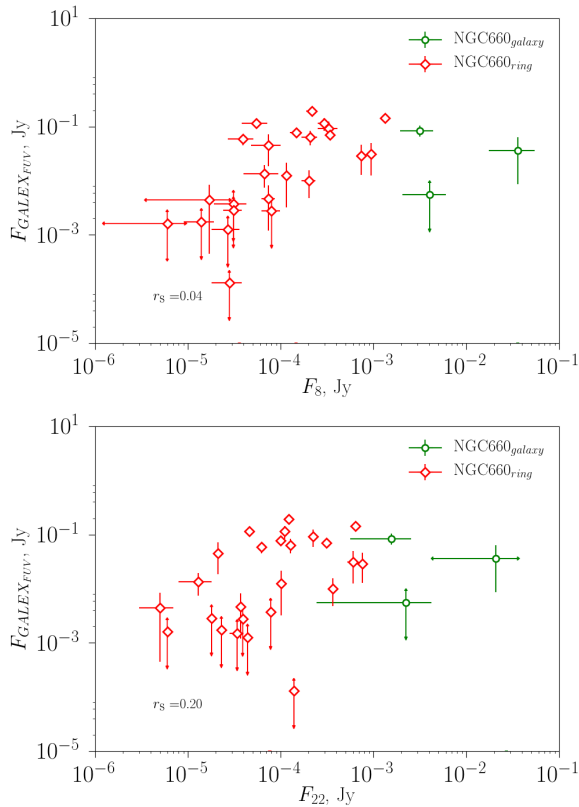
The low brightness of the IR radiation of the ring regions can be caused both by a small number of emitters (aromatic particles) and/or by a low intensity of exciting UV emission. The latter assumption can be qualitatively checked using GALEX images. To compare the emission in the IR and in the UV range, we show results of aperture photometry for Spitzer and GALEX observations in the FUV filter (data for the NUV filter show similar trends) in Figure 3. In the top panel of Figure 3, the results of UV observations are related to the 8 μm radiation. Obviously, the intensity of aromatic bands in the ring correlates well with the UV emission. The situation is less clear with the radiation from the SFRs of the galaxy disk. On the $F_8 - F_{\text{FUV}}$, diagram the disk SFRs are clearly separated from the ring SFRs. The 8 μm flux in the disk regions is nearly an order of magnitude greater than in the ring regions. At the same time, the disk SFRs are characterized by similar or even lower UV fluxes. Note also that we have only succeeded in determining the UV flux in three of five disk regions. In the other two regions, the UV emission merges with the background. The correlation of the 22 μm flux with the FUV filter flux is also visible even though it is weaker (see the bottom panel of Figure 3). Again we see the order of magnitude higher 22 μm flux in the disk SFRs coupled to the moderate UV luminosity.

The correlation between the infrared fluxes and the emission in the Hα line is weaker, which is illustrated in Figure 4. However, in this case the disk SFRs and the ring SFRs do seem to follow the same trend of having higher Hα line intensities in regions with higher infrared luminosities. The disk SFRs are noticeably brighter both in Hα and in the IR.

In addition, we calculated the Spearman correlation coefficient for all star formation regions. The numerical value of the coefficient is shown in Figs. 2, 3, and 4.
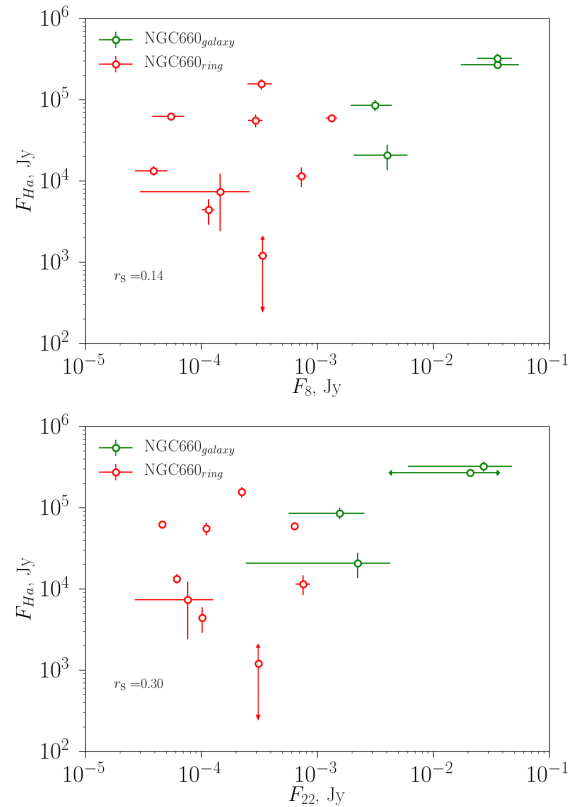
# 4 Discussion and Conclusions

Our analysis shows that SFRs in the disk and in the ring of NGC660 appear to have quite different properties. The disk SFRs are similar in their emission characteristics to SFRs in 'normal' disks and irregular galaxies studied in Smirnova *et al.* (2017). At the same time, the ring SFRs are more compact and show substantially fainter emission in the infrared bands. One may argue that this is a selection

**Fig. 3.** Comparison of aperture photometry results for SFRs in the galaxy NGC660 at wavelengths of 8 and 22 μm and the GALEX far-UV filter.

**Fig. 4.** Comparison of Hα fluxes with the 8 μm (upper) and 24 μm (bottom) fluxes.

effect as, in the ring (which is a less crowded environment), we are able to see smaller and fainter regions than in a typical galactic disk. This is an important consideration which deserves further study. However, we note that even in the dwarf irregular Holmberg II, where SFRs are quite isolated from each other, they are larger and brighter that the SFRs in the NGC660 ring (Smirnova *et al.* 2017).

The ring SFRs in NGC660 also appear to be less bright in Hα. The situation is unclear with the UV emission. The disk SFRs and the ring SFRs do overlap in the sense that the UV-bright ring SFRs are comparable (or even exceed) in luminosity to the disk SFRs. This may be related to opacity effects. If we assume that the regions that are brighter in the infrared are richer in dust, they should be more opaque in the UV band, so that there is a certain saturation effect in their UV luminosity, but this suggestion needs to be verified on a larger SFR sample. We may also start to see this effect in Hα, where there does exist a difference between the disk SFR Hα emission and the ring SFR Hα emission, but this difference is much less prominent than in the infrared.

Overall, we conclude that SFRs in the ring of NGC660 are fainter than the disk SFRs and contain less dust. At least, they are less rich in those dust particles that emit in the near- and mid-IR bands. They are also characterized by fainter Hα and UV luminosities, which may indicate their relative youth. We plan to extend this study, attracting kinematical data on the SFRs in NGC660 as well as in other galaxies with recently triggered star formation.

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