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Herschel images of NGC 6720: H_2 formation on dust grains

First results from the MESS consortium

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1. Introduction

Grains play an important role in the physics and chemistry of planetary nebulae (PNe), e.g. as catalysts for H_2 formation. We have obtained PACS and SPIRE images of NGC 6720 (a.k.a. M57 or the Ring nebula) in order to study H_2 formation. NGC 6720 is an evolved, oxygen-rich bipolar PN seen nearly pole-on. Molecules such as H_2 and CO have been detected (Beckwith et al. 1978; Huggins & Healy 1986). The central star has exhausted hydrogen shell burning and is now on the cooling track. As a result the outer halo is recombining. This object is very similar to the Helix nebula, which seems to be further advanced along the same evolutionary path (O'Dell et al., 2007). In Sect. 2 we will describe the observations, and in Sect. 3 we will discuss various scenarios for the formation of H_2. In Sect. 4 we will present the main conclusions.

2. Observations

The sub-mm images of NGC 6720 presented on this poster were obtained with the PACS and SPIRE instruments on board the Herschel satellite on 2009-10-10 and 2009-10-06, respectively, as part of the Science Demonstration Phase of the Mass-loss of Evolved StarS (MESS) guaranteed time key program (Groenewegen et al., in preparation). We also obtained a ground-based H_2 2.12 μm image with the Omega2000 camera on the 3.5-m Zeiss telescope at the Calar Alto Observatory. In Fig. 1 we present the PACS and SPIRE images and compare them to the Calar Alto H_2 image.

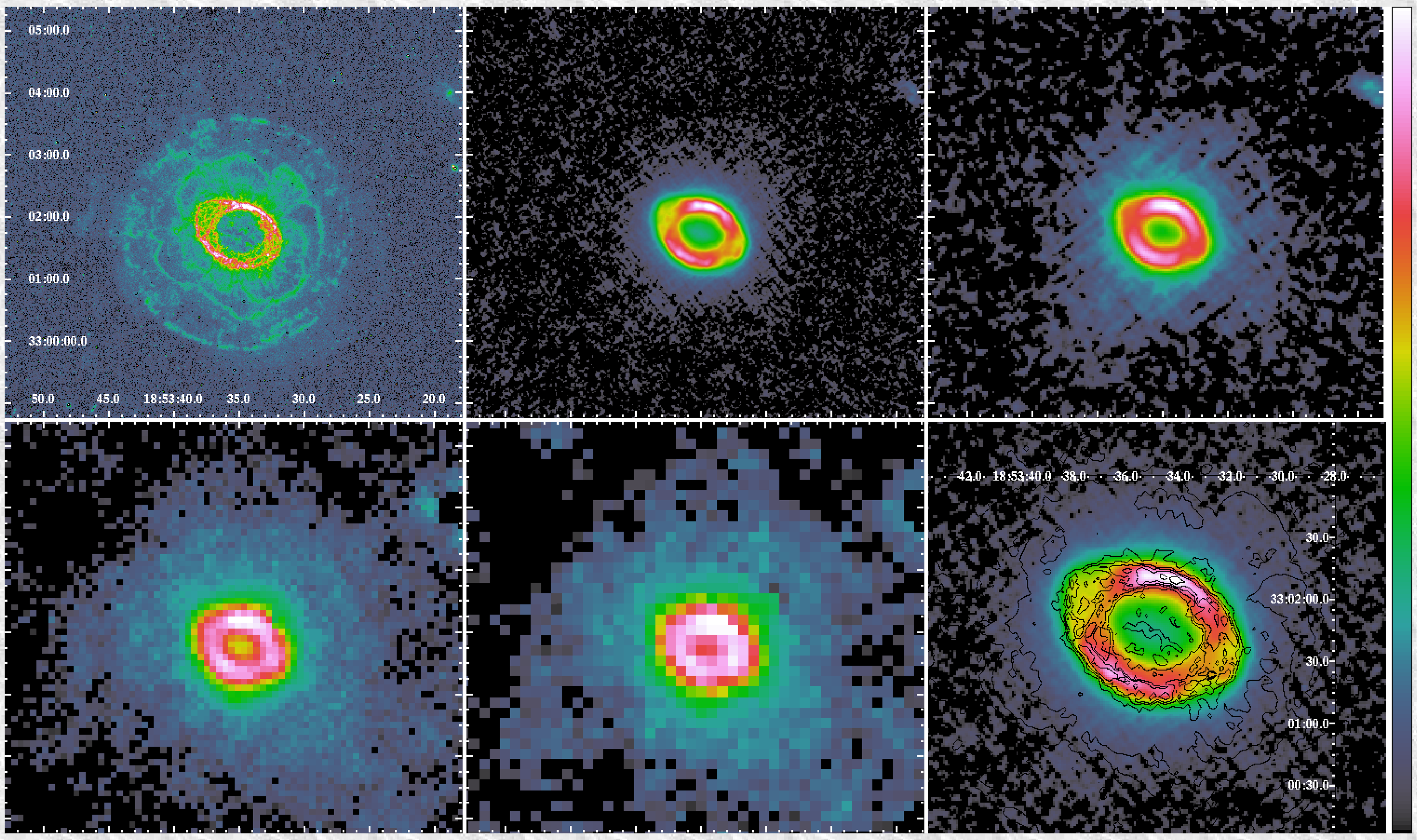

Figure 1 - NGC 6720 in five photometric bands. Top row from left to right: H_2 2.12 μm, PACS 70 μm, PACS 160 μm. Bottom row from left to right: SPIRE 250 μm, SPIRE 350 μm, and an overlay of the Calar Alto H_2 contours on the PACS 70 μm image. The H_2 image is not flux calibrated. The maps have standard orientation (N to the top, E to the left). When comparing the PACS and SPIRE images to the Calar Alto H_2 image, it becomes apparent that the morphology of the dust and the H_2 emission shows a striking resemblance even in small details. This appears to be observational evidence that H_2 forms on grain surfaces in an astrophysical environment. A similar result was obtained by Habart et al. (2003) for the ρ Ophiuchi molecular cloud, suggesting that H_2 forms on PAH surfaces. The presence of PAHs in NGC 6720 cannot be fully excluded, but seems very unlikely. Hence our observations are the first indication for H_2 formation on oxygen-rich dust grains in an astrophysical environment to our knowledge.

3. The origin of the H_2

From the ground-based H_2 images it is clear that most of the H_2 resides in high density knots in the inner ring (Speck et al. 2003). In this section we will investigate the origin of this H_2. It is clear that H_2 was formed in the dense AGB wind. In the post-AGB phase three different scenarios will be investigated: 1) this H_2 survived in the ionized region, 2) this H_2 survived in the knots, which formed before the gas was ionized and 3) this H_2 was destroyed and then was formed again later inside the knots when they formed.

3.1 Can H_2 survive in the ionized region?

For the Helix nebula, Matsuura et al. (2009) conclude that "part of the H_2 is primordial, i.e. formed during the AGB phase, and survived the ionization of the nebula". This conclusion is based on the work of Aleman & Gruenwald (2004, hereafter AG04). We recreated the models of AG04 with Cloudy, last described in Ferland et al. (1998). This code is capable of creating an equilibrium model of the ionized region as well as the PDR and the molecular regions. It includes state-of-the-art code for modeling grains (van Hoof et al. 2004) as well as the chemistry network (Abel et al. 2005) and the H_2 molecule (Shaw et al. 2005). Our H_2 model includes all ro-vibrational levels of the ground electronic state, as well as the six electronically excited states that are coupled to the ground state by permitted electronic transitions. Self-shielding of the H_2 molecule was calculated self-consistently using detailed radiative transfer (including line overlap) of each of the roughly half a million lines of the molecule. We used this code to recreate the standard model of AG04. We found that the mass fraction of H_2 in the ionized region was around 10^{-6}, somewhat lower than predicted by AG04. The expectation of AG04 that using a detailed treatment of H_2 self-shielding could increase the H_2 mass fraction by up to 2 dex could not be confirmed with Cloudy, at least not for the standard model. Most of the H_2 resides in the transition region between the H^+ region and the PDR. This amount of H_2 is insufficient to account for the observed H_2 emission in the Ring nebula.

Figure 2 - An example of the interaction of the FUV radiation field with some of the knots in the Helix nebula. Conditions are expected to be similar in NGC 6720, though it is not possible to image the knots with the same detail in this PN. This figure is taken from Matsuura et al. (2009).

3.2 Can H_2 survive in the knots?

When the photoionization of the AGB shell starts at the moment when a PN is born, the molecules in the circumstellar shell will be very quickly destroyed unless they can somehow be shielded from the ionizing radiation. Dense knots that formed during the AGB phase can provide this environment and seem a very attractive explanation for the existence of H_2 in evolved PNe such as NGC 6720. However, it is obvious from the images presented in e.g. Matsuura et al. (2009) that the FUV flux will interact with the outer layers of the knot (see Fig. 2). This interaction causes material to be advected off the knot, heating it in the process and thus causing it to shine. This process has been modeled by Henney et al. (2007). Using their models we can estimate an advection rate between 10^{-10} and 10^{-9} $M_\odot\ yr^{-1}$ for the knots in the Helix nebula. Assuming a typical mass of 1.5×10^{-5} $M_\odot$ for the knots (Meixner et al. 2005) this gives a survival time of 15,000 to 150,000 yr. However, one should realize that during most of PN evolution the central star luminosity was much higher than assumed here (by upto 2 dex, the central star of the Helix nebula has a luminosity of 120 $L_\odot$), and also that the nebula was much more compact during the early stages of evolution causing the knots to be much closer to the central star. The will cause the erosion to be much faster early on. A conservative estimate is that the survival time is at least a factor 10 shorter than stated above, and likely more. When compared to the kinematic age of the Ring nebula of 7000 yr (O'Dell et al. 2007, 2009) it becomes clear that survival of the knots over that entire period is problematic. Note that this argument also applies to models where the knots formed due to instabilities at the ionization front during the onset of ionization. More detailed modeling of the knots during the high-luminosity phase is warranted though to reach a more definitive conclusion.

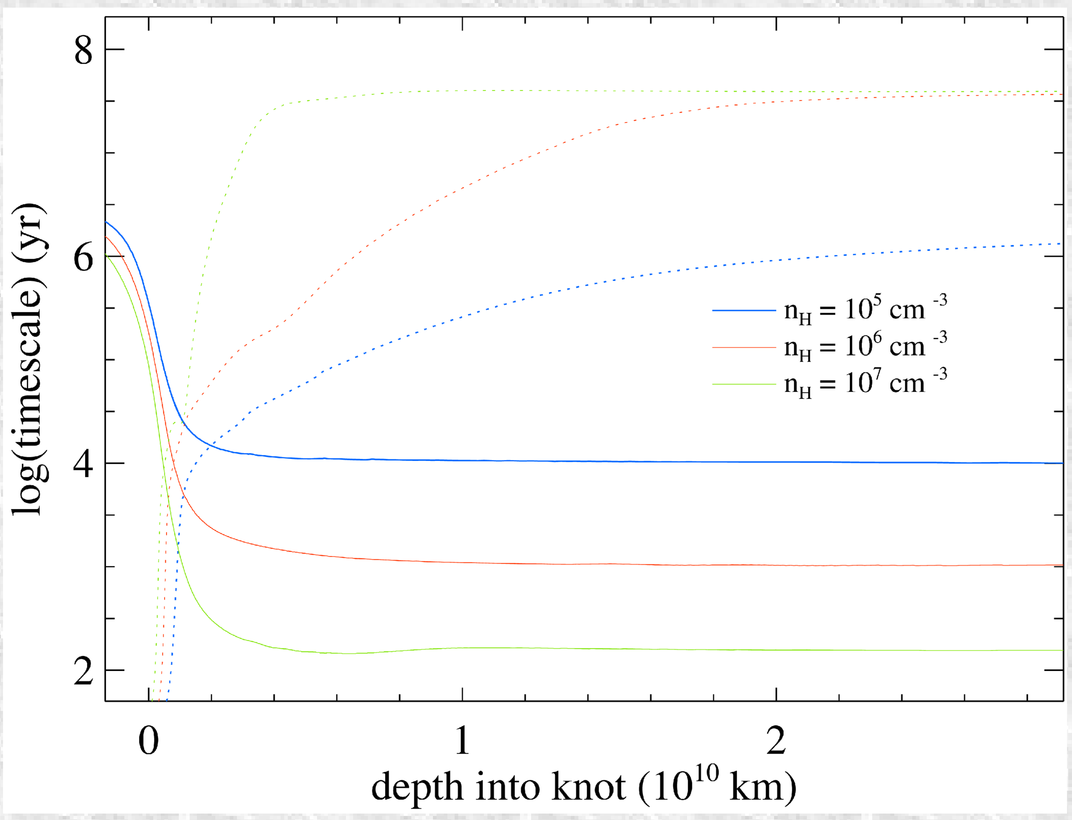

Figure 3 - The H_2 formation and destruction timescales (solid and dotted lines, respectively) for knots with a central density of 10^5, 10^6, and 10^7 cm^{-3} just outside the ionized region.

3.3 Can H_2 be formed again after ionization?

O'Dell et al. (2007) argue that knot formation only starts after the central star has entered the cooling track and the nebular material starts recombining, based on the observational fact that no similar features are seen in HST images of younger PNe. We propose a new theoretical explanation for this scenario that is based on models by Ferland & Truran (1981) which indicate that recombining gas cools very quickly, much faster than the recombination proceeds. The fast cooling would result in gas that is still ionized (and thus produces abundant recombination radiation) but has very little thermal pressure support. The radiation pressure of the recombination radiation on the dust and/or gas may then cause the medium to become unstable and fragment into many knots.

O'Dell et al. (2007) argued that the main gas phase of NGC 6720 was fully ionized during the high-luminosity phase, so that any H_2 present in the gas would have been destroyed very quickly (on timescales less than a year). Consequently any H_2 present in the knots must have formed after the formation of the knots itself started and they became dense enough to shield the molecules from the UV light. To investigate this further, we created Cloudy models of the knots. We computed eight Cloudy models with log $n_{\rm H} = 4\,(0.5)\,7.5$ to cover the full range of plausible densities in the center of the knot. From the models we extracted the formation (solid lines) and destruction timescales (dotted lines) of H_2. The results are shown in Fig. 3. The formation timescales from the Cloudy models can be summarized in the fitting formula:

$$t_{\rm H_2} = \frac{1170}{n_6^{0.9}\,\Sigma_{-21}}\ [{\rm yr}].$$

Here n_6 is the hydrogen density in the knot in units of 10^6 cm^{-3} and Σ_{-21} is the projected grain surface area in units of 10^{-21} cm^2/H. O'Dell et al. (2007) state that the central star has exhausted hydrogen-shell nuclear burning one to two thousand years ago. Given the observed core densities in the knots (3×10^5 to 10^6 cm^{-3}; Meaburn et al. 1998, Huggins et al. 2002), significant H_2 formation would be possible (though conversion from H^0 to H_2 need not be complete) assuming that the knot formation was quick after the recombination started. Hence this is currently the most plausible explanation for the presence of H_2 in the knots.

4. Conclusions

Using PACS and SPIRE images of NGC 6720 we conclude that there is a striking resemblance between the dust distribution and the H_2 emission, which appears to be observational evidence that H_2 forms on grain surfaces. We used Cloudy models of the nebula to further investigate various scenarios for the formation of H_2. We conclude that the most plausible scenario is that the H_2 resides in high density knots which were formed after the recombination of the gas started when the central star entered the cooling track. Hydrodynamical instabilities due to the unusually low temperature of the recombining gas are proposed as a mechanism for forming the knots. H_2 formation in the knots is expected to be substantial after the central star underwent a strong drop in luminosity about one to two thousand years ago, and may still be ongoing at this moment.

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