The origin of the argonium emission discovered in the Crab Nebula

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Introduction: Argonium (ArH^+) was first detected in the Crab Nebula (Barlow et al. 2013, Sci, 342, 1343) via emission in its J=1-0 and 2-1 rotational lines, and subsequently measured in absorption in the J=1-0 line along several interstellar sightlines (Schilke et al. 2014, A&A, 566, A29). Chemical modelling of the interstellar ArH^+ case by Schilke et al. (2014) found that its abundance was highest in regions with low molecular hydrogen fractions. In the Crab Nebula, ArH^+ might be present either in the transition regions between ionised gas and the photodissociation regions (PDRs) at the edge of the dense molecular H_2 clumps mapped by Loh et al. (2011, ApJS, 194, 30), or deeper within the clumps where X-rays and fast particles from the pulsar wind nebula (PWN) can produce Ar^+ (necessary for the formation of ArH^+ via the reaction $H_2 + Ar^+ \rightarrow H + ArH^+$). We present the preliminary results of a combined photoionisation and photodissociation modelling aimed at determining the origin of the observed ArH^+ emission from the Crab Nebula.

Gas and dust properties for the Crab Nebula were taken from Owen & Barlow (2015, ApJ, 801, 141) model VI, with the PWN X-ray to radio spectrum taken from Hester (2008, ARA&A, 46, 127). The UV/X-ray fluxes in the transition regions from ionised to neutral gas were calculated using a MOCASSIN (Ercolano et al. 2008, ApJS, 175, 534) model of a shell of gas located at ~2.5pc from the central source.

The dense clumps were modelled using a modified version of UCL_PDR (Bell et al. 2005, MNRAS, 357, 961) to account for the increased dust-to-gas mass ratio and the low hydrogen abundance, with the incident radiation field taken from the MOCASSIN output. An X-ray dominated region (XDR) chemical network was extended with reactions from Schilke et al. (2014), and with an argon X-ray chemistry based on methods from Meijerink & Spaans (2005, A&A, 436, 397). The output radiation field from the MOCASSIN model was converted to an incident UV field given in Draine (1978, ApJS, 36, 595) units, and an integrated incident X-ray flux for the XDR modelling.

The unmodified version of UCL_PDR was tested using the input parameters from Schilke et al. (2014), and was found to agree well with the results presented in that paper.

n_H (cm^{-3})	R (pc)	M_g/M_d	F_{UV} (Draines)	F_X (erg cm^{-2} s^{-1})
1900	0.1	28	26	0.29
n(He)/n(H)	n(C)/n(H)	n(O)/n(H)	n(N)/n(H)	n(Ar)/n(H)
1.85	1.02×10^{-2}	6.2×10^{-3}	2.5×10^{-4}	1×10^{-5}

Table 1: Properties used for modelling dense clumps in the Crab nebula, assuming the gas/dust composition of model VI in Owen & Barlow (2015) and a distance from the PWN of 2.5pc.

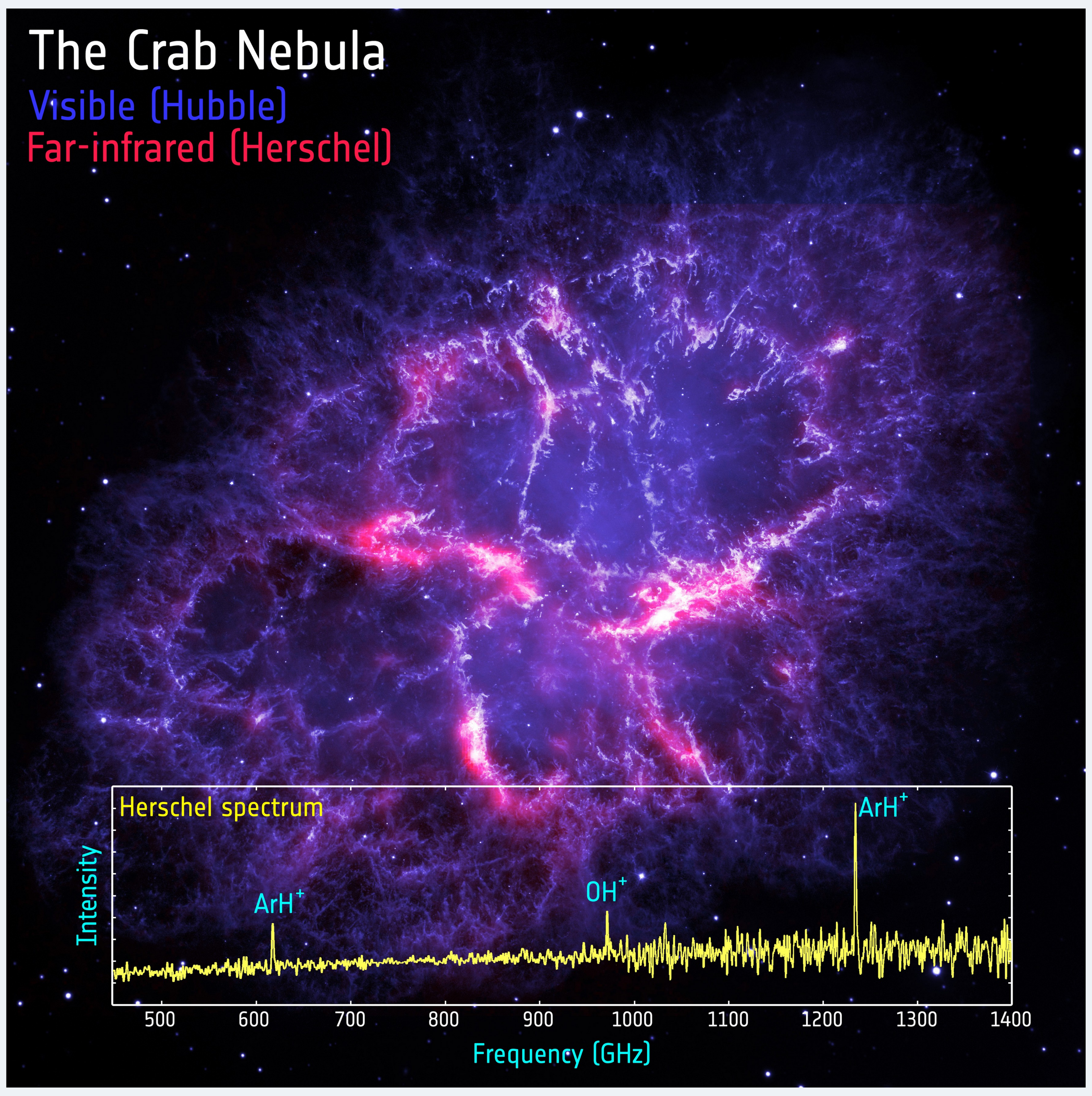

Fig 1: Image of the Crab nebula at visible and far-infrared wavelengths, and a Herschel SPIRE FTS spectrum showing the ArH+ J=1-0 and 2-1 emission lines at 617.525 and 1234.603 GHz and the J=2-1 F=5/2-3/2 OH+ rotational line at 971.804 GHz.

ArH^+ is mainly produced by reactions between Ar^+ and H_2, and is mainly destroyed by reactions with H_2. For the interstellar case (Schilke et al. 2014) it was found to be destroyed rapidly in regions with non-negligible molecular H_2 fractions, but the increased production rate of Ar^+ due to X-ray irradiation by the PWN might allow larger amounts of ArH^+ to survive in molecular H_2 zones.

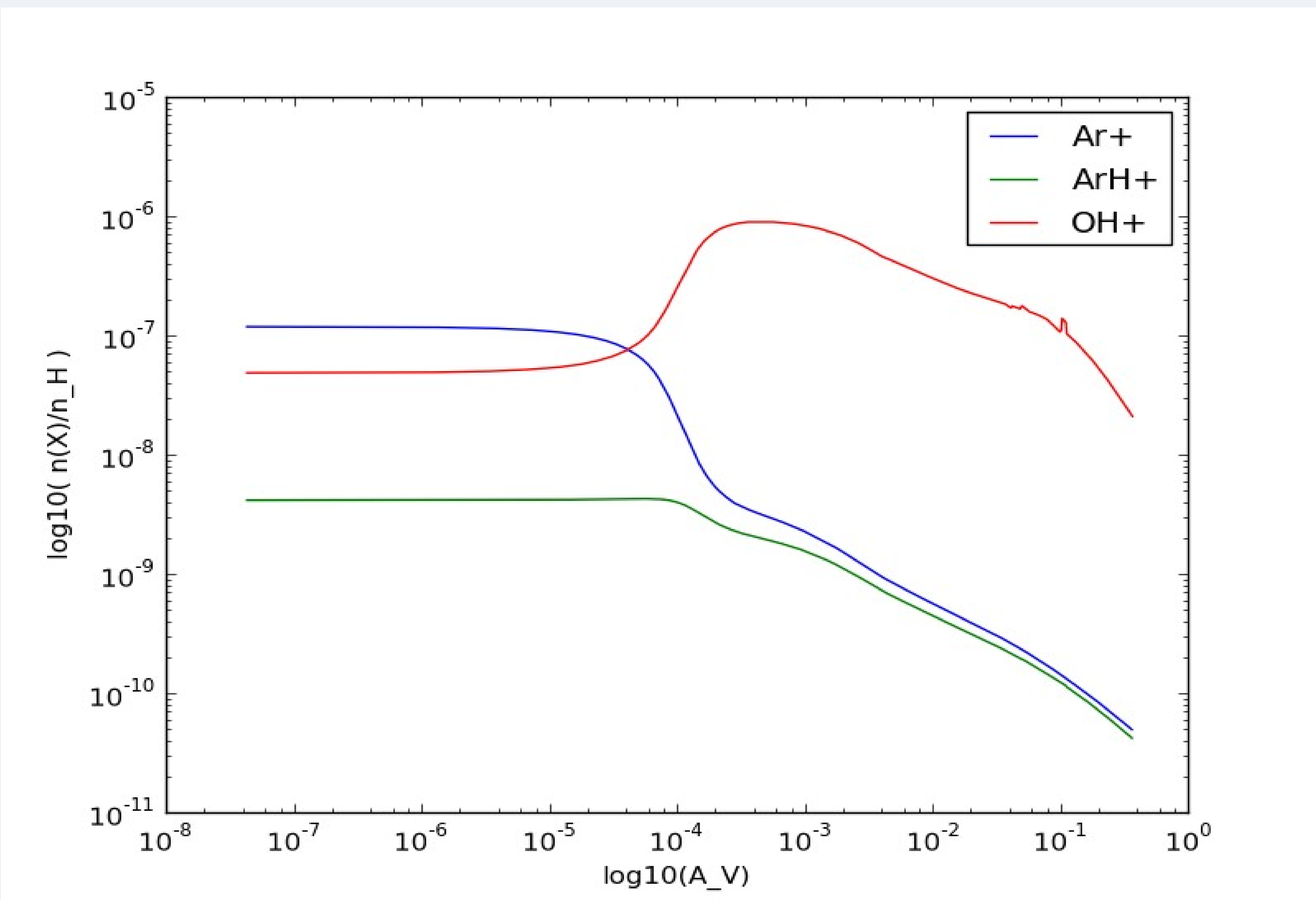

Fig 2: Ar^+, ArH^+ and OH^+ abundances as a function of visual extinction in the Crab nebula clump PDR model.

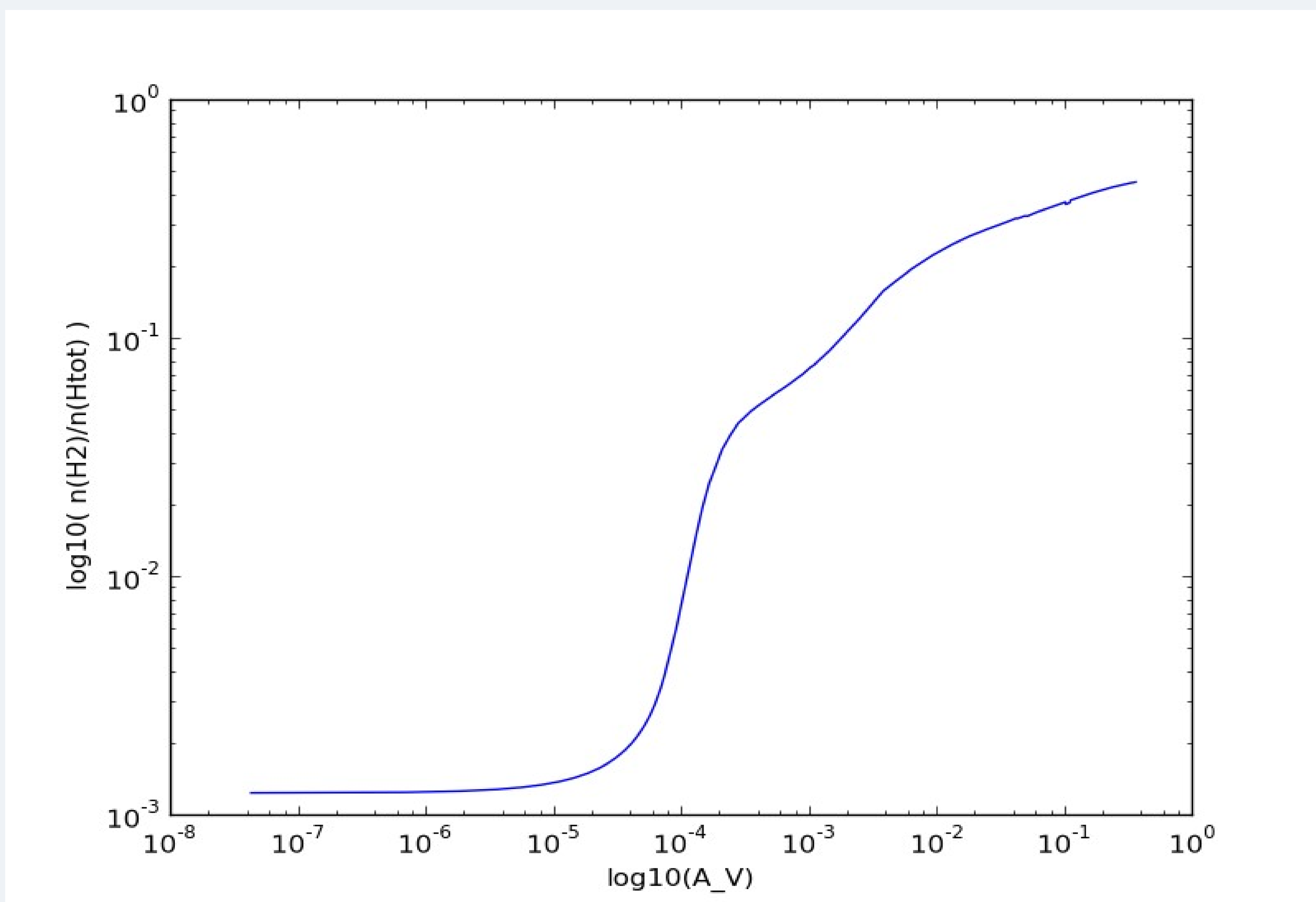

Fig 3: H_2 abundance as a function of visual extinction in the Crab nebula clump PDR model.

Conclusions: The maximum abundance of ArH^+, a few x 10^{-9} (Fig. 2), is found in the transition region between the ionised gas and the molecular clumps and, as in the interstellar case, is strongly dependent on the molecular hydrogen fraction. Significant quantities of ArH^+ only survived in regions with mostly atomic hydrogen, at the edges of the dense clumps. OH^+, also seen in emission in the Crab nebula, is most abundant in regions with higher molecular hydrogen fractions, so the emission lines likely originate from different regions to those of ArH^+. Further work is underway to investigate the effect of an enhanced cosmic-ray ionisation rate, which in the vicinity of the PWN is much higher than the standard interstellar value, and on the assumed total mass and properties of the dust grains, which affect the formation rate of H_2.