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BIODIVERSITY LOSS IN THE ORION RADIO ZOO?

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RESUMEN

Reexaminamos observaciones en radio de fuentes compactas en el núcleo de la nebulosa de Orión, encontrando que 70% de ellas corresponden a *proplyds* conocidos. Para todas estas fuentes, incluyendo muchas clasificadas anteriormente como variables y no térmicas, el flujo en radio entre 1.5 y 86 Ghz se explica plenamente por emisión libre–libre térmica del flujo fotoevaporativo. Sugerimos, pues, que muchos de los *FOXES* propuestos en Orión son en verdad *EIDERS*, y que su variabilidad aparente surge de dificultades observacionales. Resulta que los *PIGs* están extintos en Orión, y quedan elusivas las criaturas híbridas que llamamos *PANTHERS* (*proplyds* asociados con fuentes de radio no térmicas, por sus iniciales en inglés).

ABSTRACT

We re–examine radio observations of compact sources in the core of the Orion nebula and find that 70% of the sources correspond to known proplyds. For all of these sources, including many that have been previously classified as variable and non–thermal, the radio flux between 1.5 and 86 Ghz is fully accounted for by thermal free–free emission from the photoevaporation flow. We therefore suggest that many of the proposed Orion FOXES are in fact EIDERS, and that their apparent variability reflects observational difficulties in detecting the lower surface–brightness portions of the proplyds. The PIGs turn out to be extinct in Orion, and the hybrid creatures that we dub PANTHERS (Proplyds Associated with Non–THErmal Radio Sources) remain elusive.

Key Words: **H II REGIONS — INTERFEROMETRY — ISM: INDIVIDUAL (M42) — STARS: CIRCUMSTELLAR MATTER**

1. INTRODUCTION

The "Orion Radio Zoo" was first described by Garay (1987), who proposed 3 classes of compact radio sources in the inner Orion nebula: thermal DEERS (Deeply Embedded Energetic Radio Sources) and PIGs (Partially Ionized Globules, see Dyson 1968), and non–thermal FOXES (Fluctuating Optical and X–ray Emitting Sources). This work was extended by Felli et al. (1993b, herafter FTCCK), who claimed, on the basis of observed variability, that many of the supposed PIGs were in fact non-thermal, and hence FOXES. These authors also suggested that some of the thermal sources may in fact be EIDERS (Externally Ionized Disks in the Environs of Radiation Sources), rather than PIGs.

In the present work, we re–assess the corpus of Orion radio observations in the light of detailed photoevaporation models, which have been previously fitted to optical emission line imaging and spectroscopy of the proplyds (Henney & Arthur 1998; Henney & O'Dell 1999, hereafter HA98; HO99). The current status of the photoevaporation models is summarized in Henney, this volume. Our work will be described in more detail elsewhere.

2. COMPARISON OF Hα AND 2 CM FLUXES

Figure 1 shows the observed correlation between Hα flux and 15 GHz flux for 26 proplyds. We measured the Hα fluxes from HST WFPC2 images (O'Dell 1998; Bally, O'Dell & McCaughrean 2000) and corrected them for

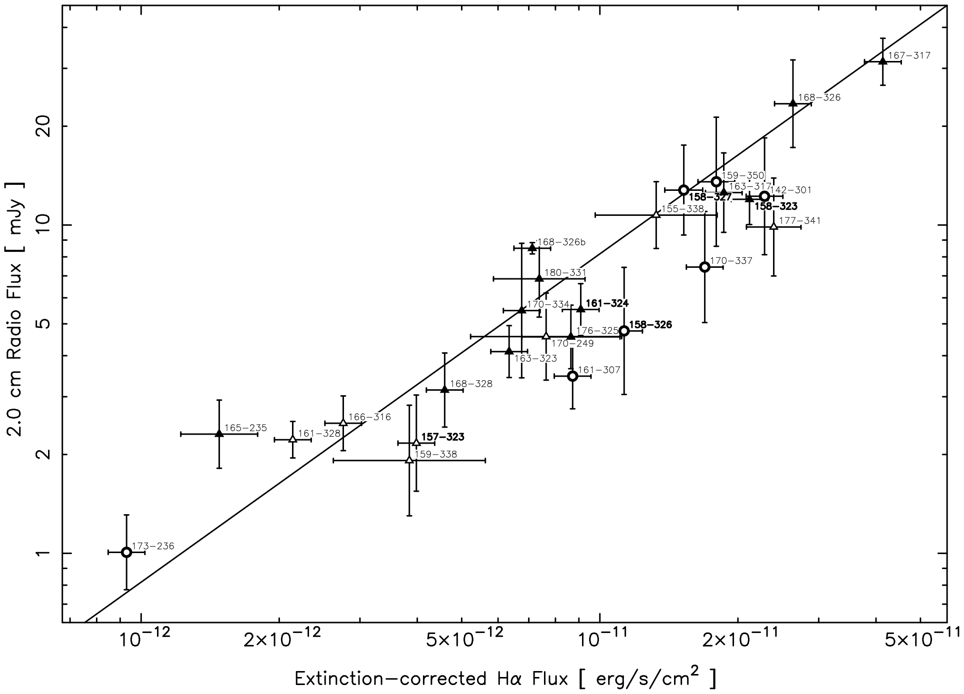

Fig. 1. Observed radio flux at 15 GHz versus extinction–corrected Hα flux for all proplyds with 15 GHz detections. Different plot symbols denote the classification of the sources by FTCCK of nonthermal (hollow circles), thermal (filled triangles), and uncertain (hollow triangles). The sources shown in Fig. 2 are shown in bolder type. The straight line shows the expected relation for optically thin free–free emission.

foreground dust extinction (O'Dell, Walter & Dufour 1992). The 15 GHz fluxes were taken from the literature (Garay, Moran & Reid 1987; Churchwell et al. 1987; Felli et al. 1993a, hereafter FCWT; FTCCK) and the vertical error bars show the RMS variation between individual measurements of the same source. Whether such variation really reflects an intrinsic *variability* of the source is discussed further below.

The solid line on the graph shows the relation $F_\nu = 8.71 \times 10^{11} T_4^{0.55} \nu_{15}^{-0.1} F_{\mathrm{H}\alpha}$, which is expected for optically thin thermal emission, where F_ν in in mJy, $F_{\mathrm{H}\alpha}$ is in erg s^{-1} cm^{-2}, T_4 is the gas temperature in units of 10^4 K (we assume $T_4 = 0.89$), and ν is the frequency in units of 15 GHz. It can be seen that the observations reproduce the expected relation very well (see also McCullough et al. 1995), although falling somewhat below it in the sense that the 15 GHz flux is, on average, slightly less than that predicted from Hα. It is particularly noteworthy that none of the sources classified as "nonthermal, variable, stellar emitters" in FTCCK (shown by hollow circles) have 15 GHz fluxes significantly in excess of the expected thermal value.

In Figure 2(a,b), we compare Hα and 15 GHz images of a small $(6 \times 6'')$ region to the West of θ^1 C Ori, that is particularly rich in proplyds. In Figure 2(c), we show the result of simulating the radio map on the basis of the Hα image. For each pixel in the Hα image, after correcting for foreground dust extinction, we calculated the 15 GHz free–free optical depth and hence the 15 GHz surface brightness, assuming isothermal emission at 8900 K. We added random noise to reproduce the RMS noise/beam of the radio map and convolved with a Gaussian to account for the slightly lower radio resolution. Finally, we convolved with an inverted top–hat function to simulate the 40 Kλ baseline cut–off. The similarity between the observed and simulated radio maps is quite remarkable, providing further evidence that the majority of the proplyd 15 GHz emission is indeed thermal. Of the five proplyds in the field, 158–327, 158–326, and 157–323 were classified as "non–thermal" by FTCCK, but none of these show any significant radio emission in excess of the prediction based on Hα.

Closer inspection of Figure 2 sheds some light on why the 15 GHz flux of many proplyds seems to lie *below* the thermal line in Figure 1, and on a possible explanation for the observed "variability". The observed Hα flux of the proplyd 158–326 is larger than that of 161–324 and smaller than that of 158–327, but its surface brightness is the lowest of the three, since 161–324 is much more compact. As a result, in both the simulated and observed 15 GHz maps, 158–326 barely pokes its head above the noise, whereas 161–324 is detected much more strongly and appears to be a larger source than 158–326. This leads to the radio flux of 158–326 being underestimated by a factor of 2–3, simply because its $(\simeq 1'')$ extended emission is buried in the noise. It seems very likely that this "tip–of–the–iceberg" effect will vary in its severity between different observations, depending on the exact configuration used, atmospheric conditions, and so on. In this way, the apparent flux

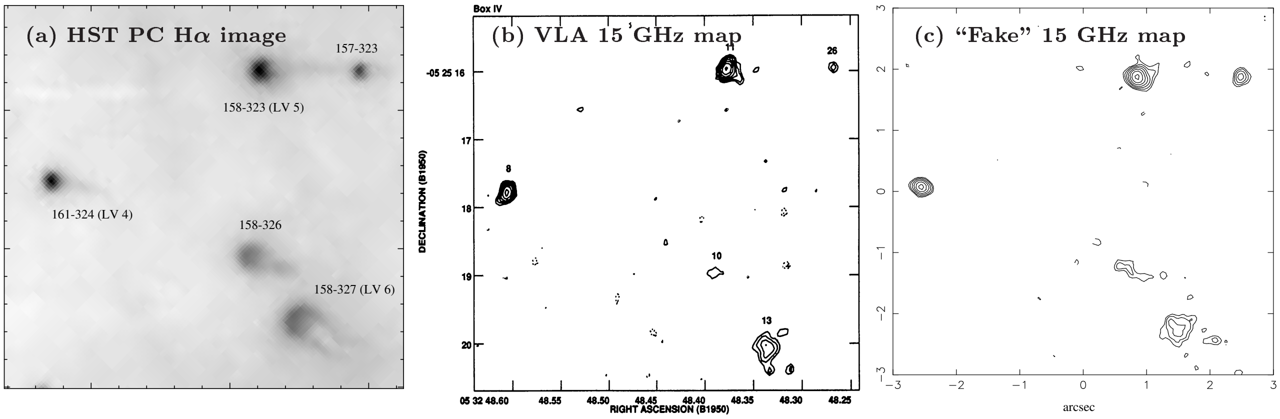

Fig. 2. (a) Flux–calibrated, continuum–subtracted, HST WFPC2 image in the F653N filter of the region, approximately 5″ West of θ^1 C Ori, that contains the proplyds LV 4–6 (O'Dell 1998), shown with a logarithmic stretch. (b) A–configuration VLA map at 15 GHz of the same region from FCWT, with a 40 Kλ cut–off. Beam width is 0.14″, contour levels are [−0.7, −0.5, 0.5, 0.7, 1.0, 1,41, 2.0, 2.82, 4.0] mJy/beam. (c) Simulated 15 GHz map, created from the Hα image in panel (a), as described in the text. Contour levels are the same as in panel (b).

variability (of order 50%) observed by FTCCK in many of the sources now known to be proplyds can easily be produced by this effect. Indeed, the maximum flux for 158–326 reported by FTCCK is about 10 mJy, which would lift it up almost exactly to the thermal line in Figure 1.

3. OBSERVED SPECTRA

Figure 3 shows spectra of 6 of the brighter proplyds, containing all published radio fluxes from 1.5 to 86 GHz. The upper row of sources are all classified as "thermal" by FTCCK, while the lower row are classified as "non–thermal" or, in the case of 177–341, "uncertain". The solid lines show the predicted spectra from the Hα–constrained photoevaporation models, after correcting for the "camouflage" effect on the interferometric fluxes of the background nebular emission (Pastor, Cantó & Rodríguez 1991). Note that these spectra have been in no way "fitted" to the radio spectra. For the upper row of sources, the models show generally good agreement with the spectra. (The wayward points at 1.5 GHz in 168–326 and 158–323 have reported source sizes many times larger than the proplyds, indicating severe contamination by nebular emission.) The lower row of sources show large temporal variations in flux, especially at 15 GHz, but always *below* the thermal curve. This is further evidence that the variation is due to the "tip–of–the–iceberg" effect discussed above. It is perhaps no coincidence that the variable sources are generally larger and have lower surface–brightness. The high 1.5 GHz flux of 158–327 is perhaps an indication of a non–thermal component, but again the reported source size is very large (3″ with a 1″ beam), making it doubtful that the emission comes from a star.

4. DISCUSSION

Of the 42 compact radio sources in the core of the Orion nebula listed by FTCCK, 29 can be identified as known proplyds from the lists of O'Dell & Wong (1996) and HA98. Since all the proplyds are photoevaporating star–disk systems, they should be classified as EIDERS, rather than PIGs. Indeed, there would seem to be no PIGs in the Orion nebula. For all the proplyd sources, the vast majority of the radio flux must be due to thermal emission from the same gas that gives rise to the Hα emission line. Although many of these sources are listed as "non–thermal, variable, stellar emitters" in FTCCK, our results show that there is no detectable non–thermal emission at 5 or 15 GHz and that the apparent variability at these frequencies is an observational artefact. On the other hand, FTCCK detected at least 4 bona fide FOXES (their sources F, G, M, & N), spatially coincident with non–proplyd T–Tauri stars. Since almost half the low–mass stars in

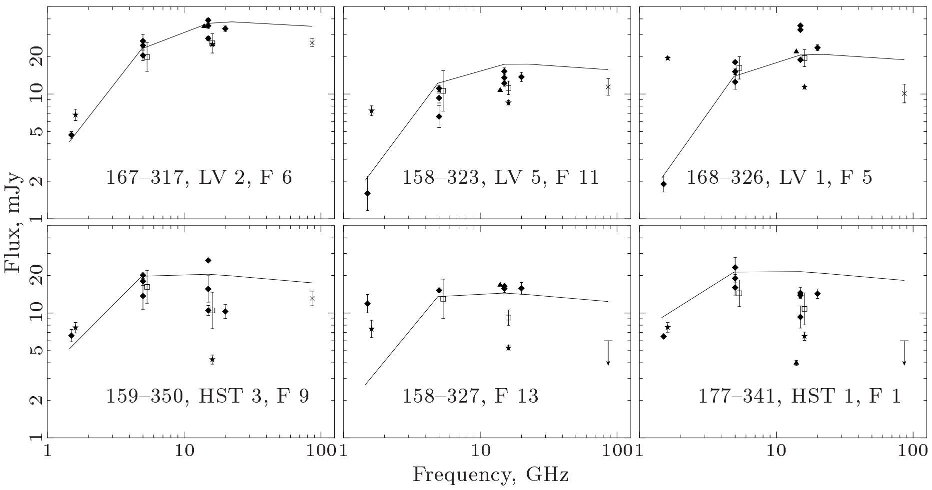

Fig. 3. Radio spectra of 3 proplyds classified as thermal by FTCCK (upper panels), and 3 proplyds classified as non–thermal (lower panels), compared with predicted free–free spectrum (solid line) from the photoevaporation models fitted to the proplyd Hα images. Data are from Garay, Moran & Reid (1987), Churchwell (1987), FCWT, FTCCK, and Mundy, Looney & Lada (1995).

the inner Trapezium cluster are proplyds, one would expect a similar number of hybrid beasts, for which we propose the name PANTHERS (Proplyds Associated with Non–THErmal Radio Sources). However, we find no firm evidence for any such creatures in the published data. This may be partly because any chromospheric emission from the enclosed T–Tauri star would be strongly absorbed at low frequencies (≤ 5 GHz) by the optically thick thermal gas in the photoevaporation flow.

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