Resolving Circumnuclear Star Formation in M100 with Image Stabilisation at *UKIRT*

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Abstract

Near-infrared (JHK) images of the nucleus of the barred spiral galaxy M100 (NGC 4321) have been obtained using a high-bandwidth tip-tilt secondary and fast guider system on the 3.8m United Kingdom Infrared Telescope (*UKIRT*). The resulting images, with a resolution of $0\farcs34$ at K, reveal for the first time a host of compact "knots", which appear to be the result of a recent burst (or bursts) of star formation. Confirmation of this comes from K-band spectroscopy of these knots with CGS4 on *UKIRT*, which shows Brγ emission and CO absorption features. A comparison with starburst evolutionary models suggests ages for these knots of 15–25 Myr, and a stellar population dominated by late-type supergiants.

1 The Upgraded *UKIRT*

In an effort to deliver image quality which is as close as possible to the diffraction limit (FWHM = $0\farcs11$ at λ =2.2 μm), the 3.8m United Kingdom Infrared Telescope (*UKIRT*) has been upgraded with the addition of several new features (Hawarden et al. 1998), including:

- A high-bandwidth tip-tilt secondary mirror driven by a Fast Guider sampling at rates up to 100 Hz, supplied by the Max Planck Institut für Astronomie (MPIA), Heidelberg.
- Low-order active control of the primary mirror, calibrated with monthly wavefront sensing measurements, and active focus control.
- A set of 16 louvred apertures in the dome itself to assist natural dome flushing by wind, or by a forced ventilation system.
- Primary mirror cooling, and dome floor insulation (both yet to be implemented).

Together, these upgrades have resulted in a median seeing of $0\farcs45$ at K.

2 Near Infrared Imaging of the Nucleus of M100

As part of an ongoing effort to understand the relationship between circumnuclear star formation, nuclear activity, and gas flows within the central regions of barred spiral galaxies, we have been carrying out high-resolution observations in the optical, near-infrared, and radio regimes of a sample of nearby barred spirals. We have assembled a fairly extensive dataset ($UBVRIK$ and Hα, *Hubble Space Telescope* V-band, and CO molecular emission) for M100 (NGC 4321), the brightest spiral galaxy in the Virgo cluster (Knapen et al. 1995a, b). Efforts to obtain images in the K-band with a resolution approaching that of the HST optical

Table 1: Line Equivalent Widths (nm) in Selected Regions of M100

Object	Brγ	H_2 2.122 μm	CO_{sp}
Nucleus	<0.3	0.3	0.24
K1	0.4	0.3	0.32
K2	0.3	0.2	0.30

images using the Adaptive Optics Bonnette PUEO at the Canada-France-Hawaii Telescope (Rigault et al. 1998) have met with only limited success, due mainly to the lack of a suitable natural guide star. Therefore, we hoped to take advantage of the improved delivered image quality of *UKIRT* and its active optics system.

Images in J, H, and K of the nuclear region of M100 were obtained on 1998 February 14 UT, when the seeing was measured at $0\farcs34$ in the K-band from bracketing observations of standard stars. A 2× magnifier was attached to IRCAM3 on *UKIRT*, yielding $0\farcs14$ pixels. Fig 1 compares our new image with the previous best K image of M100 (Knapen et al. 1995a)

Photometry of each of the 41 distinct knots visible in all 3 bands was performed using the CCDCAP digital circular aperture photometry code (Mighell 1997). Since many of the knots could be severely reddened by their proximity to the dust lanes, a first-order correction for reddening was made by measuring the colour excess in $I-K$ of the background stellar population around each knot (from data in Knapen et al. 1995a), and then assuming the reddening is the same towards the knot. The distribution of corrected knot NIR colours is shown in Fig. 2, along with a reddening vector and symbols representing the typical NIR colours of an old stellar population, a 300 Myr old burst population, and 300 Myr of continuous star formation.

The K-band Luminosity Function (LF) of these knots, also corrected for extinction, and assuming a distance to M100 of 16.1 Mpc (Ferrarese et al. 1996) is presented in Fig. 3. Although this LF is not unlike that typical of extragalactic globular cluster systems (the superimposed Gaussian having $\langle M_V \rangle = -7.1$, $\sigma(M_V) = 1.3$ (Harris 1991), and $\langle V-K \rangle = 6.9$), we point out that this would require the stellar content to be totally dominated by dwarfs or giants of type M6 or later. There is also a clear deficiency of bright objects if, indeed, these knots are globular clusters. In any case, we note that a single knot with $M_K = -14$ would require up to 25000 K4 giants, or as few as just 70 M0 supergiants, to account for the observed luminosity.

3 NIR Spectroscopy

Spectroscopy of the two "hot-spots" at each end of the central bar (labelled K1 and K2 by Knapen et al. 1995a) and the nucleus was obtained on 1998 February 12 with CGS4 on *UKIRT* at a resolution $R \sim 350$. Equivalent widths (nm) of Brγ and H_2, and the spectroscopic CO 2–0 index (Doyon, Joseph, & Wright 1994) are given in Table 1. These results indicate that K1 and K2 are at a similar evolutionary stage, and in contrast to the nucleus, show evidence of recent massive star formation. Thus, at least in the knots associated with K1 and K2, massive star formation has taken place within the last 100 Myr.

A comparison of the Brγ and CO equivalent widths with starburst evolutionary models in the literature (Leitherer & Heckman 1995; Puxley et al. 1997) indicates that star formation in the knots associated with the hot-spots K1 and K2 was triggered in bursts 15–25 Myr ago, consuming $\sim 10^5$ $M_\odot$ of gas per knot. From the modelling and observations in Knapen et al. (1995b), we know that the circumnuclear region hosts two small-scale, but relatively strong, density wave spiral arms. Starbursts can occur in the spiral armlets, induced by the concentration and compression of abundant gaseous material by the density wave

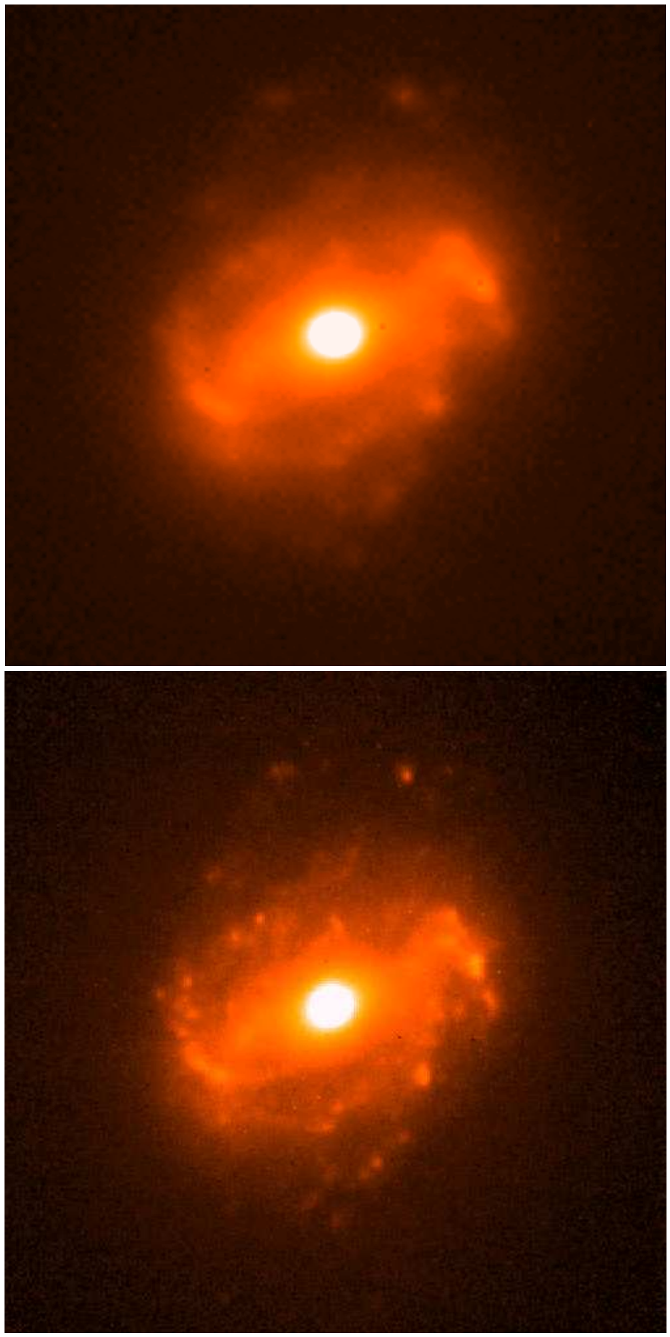

Figure 1: Comparison of the best previous *UKIRT* 2.2 μm image of the inner 35 arcsec (2.7 kpc) of M100 (*top*; Knapen et al. 1995a) with our new image (*bottom*) from Feb 1998. The "lumpy" structures at either end of the central bar (designated K1 and K2 by Knapen et al.) are now resolved into numerous compact "knots".

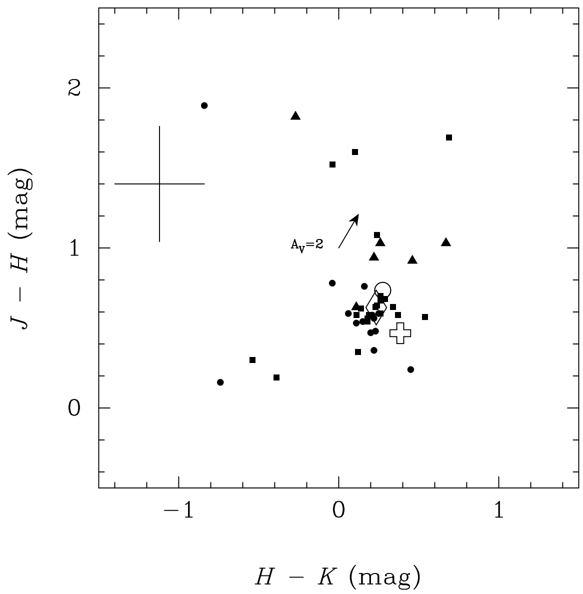

Figure 2: NIR colour-colour diagram for the knots in M100, after de-reddening. A typical error bar is shown at upper left. The reddening vector corresponding to A_V =2 mag is also shown. The open symbols mark the expected colours for a 10 Gyr old stellar population (circle), a 300 Myr old burst (diamond), and 300 Myr of continuous star formation (cross). The filled triangles, squares, and circles indicate knots embedded in, adjacent to, or well outside of the dust lanes, respectively.

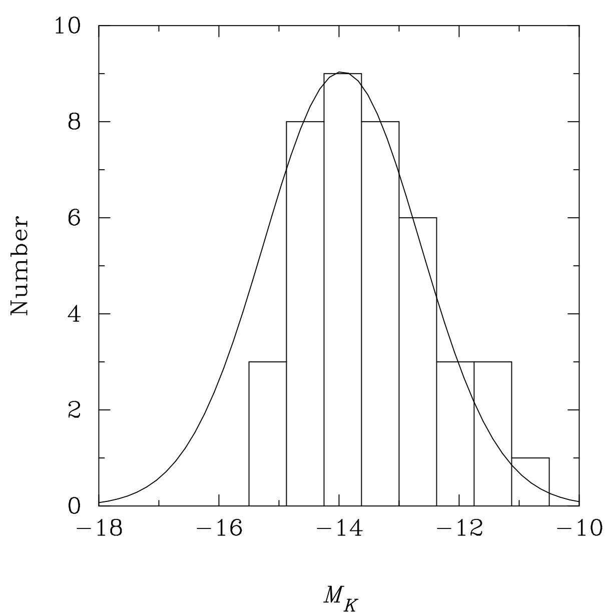

Figure 3: The K-band Luminosity Function (LF), after individual corrections for extinction. Superimposed is the Gaussian LF expected for extragalactic globular cluster systems with $\langle M_K \rangle = -13.95$; note the apparent deficiency of bright clusters.

amplified by the gas self-gravity, and show up first as H II regions, and after $\sim$ 5 Myr, start emitting strongly in K (Leitherer & Heckman 1995; Knapen 1996). The distribution of knots in the circumnuclear region is compatible with, and fully explained by, the interaction of disk gas with the non-axisymmetric (barred) potential in M100.

A difference in the stellar populations of the knots relative to the unresolved nuclear light also has implications for dynamical analyses. Our results confirm the variations in M/L_K over the circumnuclear region of M100 derived in Knapen et al. (1995b), and quantified by the dynamical modelling of Wada et al. (1998).

More details of our observations and analysis can be found in Ryder & Knapen (1999).

4 Conclusions

The improvements in delivered image quality at *UKIRT*, *using only active optics*, have already helped show us the location, and given us clues about the nature of circumnuclear star formation in M100. At least 40 distinct "knots" can be identified in our NIR images, scattered over the central kiloparsec or so. On the basis of the NIR colours alone, these knots would be almost indistinguishable from an old stellar population. However, the presence of NIR emission lines, and deep CO absorption features in at least two of them, indicates they are actually the sites of recent star formation. In particular, two of the knots associated with the previously-identified hot-spots K1 and K2 have ages of between 15 and 25 Myr. Followup spectroscopy of more of these knots should reveal whether they were formed in a single burst, or triggered sequentially by some dynamical process.

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