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The Largest Known Planetary Nebula on the Sky

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The enormous Sloan Digital Sky Survey (SDSS) spectroscopic catalogue has many applications but the discovery of Planetary Nebulae (PN) had not been recognised as among the potential scientific returns. However, the INT recently played a key role in the identification of a record breaking PN discovered serendipitously from the SDSS.

The vast majority of PN in our own galaxy have been identified via wide-field narrow-band Hα surveys of the type currently ongoing using the INT (`http://astro.ic.ac.uk/Research/Halpha/North/`) or through wide-field low-resolution slitless spectroscopic surveys, with both techniques attempting to isolate objects showing very high equivalent width emission lines that are characteristic of PN. The potential of the relatively high-resolution, pointed spectra that make-up the SDSS spectroscopic database involved a serendipitous observation during the course of a search for high-redshift gravitational lenses. The idea behind the gravitational lens search is to target luminous (massive) galaxies at intermediate redshifts, $0.2<z<0.6$, which constitute the optimal line-of-sight for detecting gravitationally lensed background sources (Hewett et al., 2000). The population of high-redshift star-forming galaxies, many of which possess strong Lyα emission, provide a high surface density of readily detectable background sources. The first such object was discovered by Warren et al. (1996) and the application of the SDSS survey for lenses at lower redshifts has been demonstrated by Bolton et al. (2004).

Examining the results of an automated search of the SDSS DR1 spectroscopic database for emission lines from putative high-redshift sources, one particular galaxy showed an unambiguous emission line detection with a somewhat weaker feature to the blue. The emission line pair was immediately identifiable as emission from [OIII] 4959, 5007. Not an entirely unexpected occurrence but the unusual feature of the detection was that the wavelength of the detection placed the emission at essentially zero radial velocity. Querying the output of the emission line search for similar detections produced more spectra showing a similar signature. All of the objects possessing [OIII] emission occurred in an approximately circular region with a diameter of ~1.5°, with not a single detection anywhere else on the sky. Investigation of SDSS spectra of stars, quasars and even sky fibres revealed further detections, all concentrated in the same region of sky.

A series of checks fairly rapidly eliminated the majority of instrumental artifacts or transient phenomena as the cause of the emission. Discrete enquires of the SDSS team produced the news that [OIII] emission had occasionally been detected but this was due to auroral activity. However, the detection of the [OIII] emission in two SDSS spectroscopic fields observed on different nights and confirmation

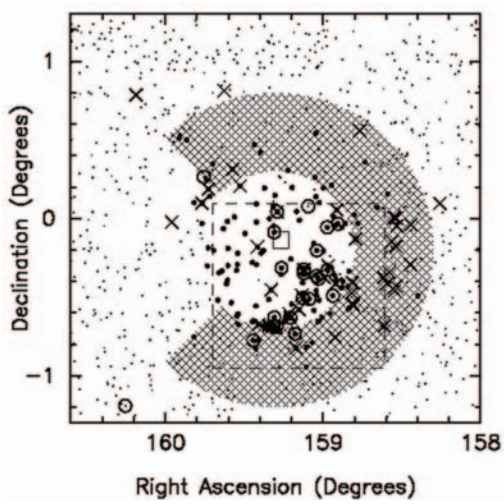

Figure 1. Spatial distribution of spectra with detectable [OIII] 4959, 5007 (dots), Hα (circles), and [NII] 6583 (crosses). The hatched area indicates a region where composite spectra also show unambiguous evidence of [OIII] 4959, 5007 emission. Positions of objects with SDSS spectra for which no individual detections were obtained are also indicated. The dashed outline shows the area included in the narrow-band images of Figure 2. The location of the white dwarf PG 1034+001 is marked by a box.

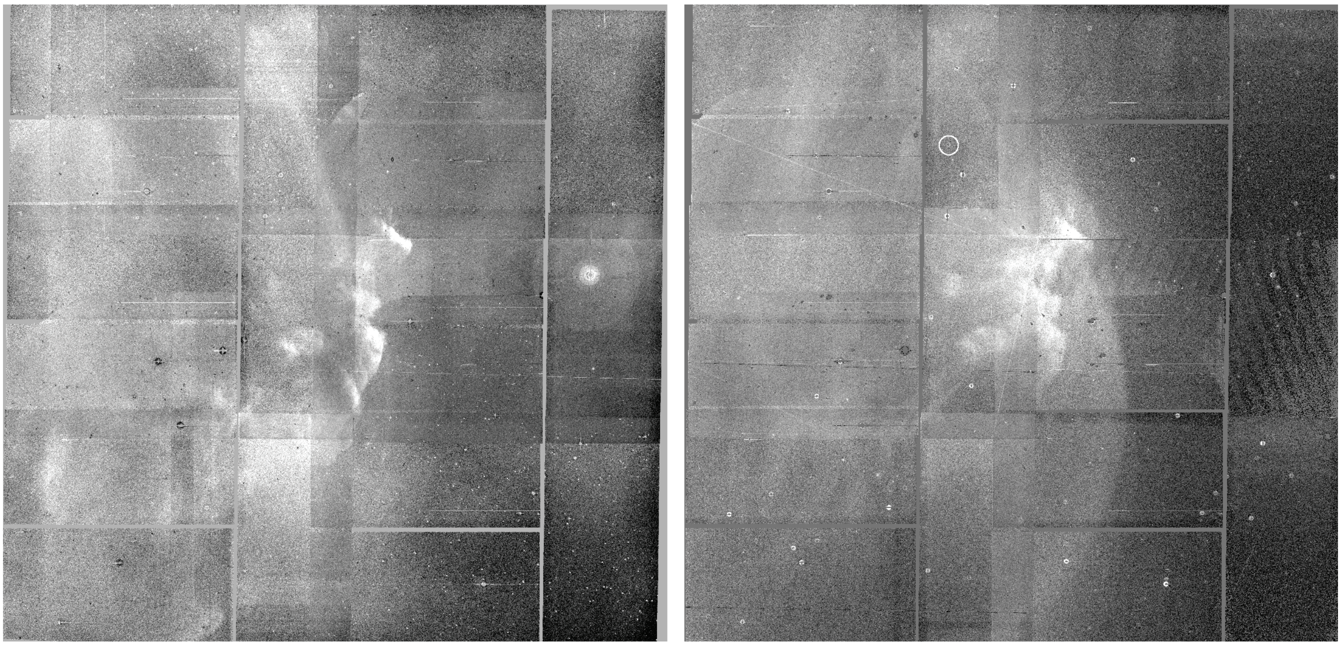

Figure 2. The left hand panel shows a mosaic of 6 INT WFC continuum–subtracted pointings in Hα+[NII] while the right panel shows the equivalent for [OIII]. The images are approximately 0.8° on a side with North to the top and East to the left. The location of the white dwarf PG 1034+001 is indicated by a circle in the [OIII] image. Emission with complex structure is evident in the central regions of the images in both passbands. A well–defined arc, or boundary, is visible at center–right in the [OIII] image.

of the continued presence of [OIII] emission from a spectrum obtained at the MMT Observatory ruled out an explanation due to a transient phenomenon. Combining spectra beyond the boundaries of the region where [OIII] emission was detected in individual produced clear detections of [OIII] emission extending over a region more than 2° in diameter.

A smaller number of individual spectra also showed the presence of emission from Hα and [NII] 6548, 6583. The spatial distribution of the individual emission line detections revealed clear trends and composite spectra, made up from objects contiguous on the sky, confirmed the trends and even allowed the detection of [SII] 6718, 6732. Figure 1 shows the spatial distribution of line emission as derived from the SDSS spectra.

Narrowband imaging of the central part of the region was undertaken during a WFC survey run on the INT in 2003 May. The object is hard work, with integrations of 1200 and 2700 s in Hα and [OIII] 4959, 5007 respectively, necessary to allow the detection of emission over the majority of the field. However, the results were unambiguous, with excellent agreement between the surface brightness distribution evident in the INT images (Figure 2) and the emission line detections from the SDSS spectra. A striking feature of the images was the presence of a well-defined arc-like feature, perhaps suggestive of some form of shock.

A wide range of possible explanations for the emission line region were considered without success. Then, following the INT observations, a search of the region using SIMBAD revealed the presence, close to the region with the strongest [OIII] emission, of a very nearby, extremely hot DO white dwarf (PG 1034+001). The location of the white dwarf clinched the identification of the emission region as a PN. The diameter of more than 2° makes the object the largest known PN on the sky and Rauch et al. (2004) have identified evidence for an ionised halo some 10° across.

PG 1034+001 does not yet possess a parallax distance but the spectroscopic distance estimate of 155^{+58}_{-43} pc (Werner et al., 1995) means the PN is certainly the second closest known and a parallax distance could confirm the nebula as the nearest PN to the Solar System. The unambiguous detection of a PN associated with a non-DA white dwarf is also a first. Determination of a reliable age for the PN will help constrain timescales associated with the late stages of evolution of post-asymptotic giant branch stars and the origin of helium-rich white dwarfs. The PN is certainly old, an estimate of the expansion age and a kinematic age estimate, derived from extrapolating the observed proper motion of PG 1034+001 back to the origin of the radius of curvature of the arc feature, both suggest an age of ≅100,000 yr. The strongly enhanced [NII] emission evident along the south western boundary of the PN is also indicative of the interaction of an old PN with the surrounding interstellar medium.

The strength of the [OIII] emission suggests that imaging of other hot non-DA white dwarfs might be rewarding and we have begun such a programme with the INT in collaboration with Matt Burleigh (Leicester). The first run earlier this year suffered from poor conditions but preliminary results suggest the detection of at least one new PN. ¤

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Exploring Andromeda's Halo with the INT

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The structure of the outer regions of galaxies is a key area in which to look for fossil remnants of the accreted masses from which the galaxies that we see today are thought to be built (Searle, 1978, White, 1978). The importance of these regions has increased in recent years as cosmological theories of structure formation become more exact in their predictions, and the observational instrumentation required to conduct these detailed analyses becomes more sophisticated. Currently composed of 165 individual pointings of the Isaac Newton Telescope Wide Field Camera (INT WFC), the M31 halo survey consists of photometry for over 7 million sources, on a photometric system accurate to 2% over ~40 square degrees on the sky, in some places probing the halo of Andromeda out to 6° (~80 kpc). Observations of 800–1000 seconds in the Johnson V (V′) and Gunn i (i′) passbands are deep enough to detect individual RGB stars down to V′= 0 and Main Sequence stars down to V′=−1. This unique dataset has provided, for the first time, a panoramic deep view of the stellar halo of a giant galaxy *thought* to be similar to our own Milky Way (Irwin, 2004).

The initial results of this survey could not have been more surprising: despite exhibiting a near pristene disk, M31's halo is full of substructure and points to a history of accretion and disruption (Ferguson, 2002). Figure 1 shows an image of M31, constructed from the WFC photometry, which shows the inhomogeneity of this system. Metal-poor/young stars are coded blue whilst metal rich/older stars are coded red. This spectacular image shows in amazing detail the wealth of information that the INT is helping to reveal about the structure of this previously invisible region of galaxies. The most obvious piece of substructure visible in Figure 1 is the giant stellar stream (visible in the south-east). This extends to near the edge of our survey —a projected distance of some 60 kpc (Ibata, 2001). In fact, by examining the systematic shift in the luminosity function of the stream as a function of galactocentric radius, we find its actual length is much greater than 100 kpc (McConnachie, 2003). The similarity of the colour of this feature with the loop of material at the north of the survey suggests a connection: deep follow-up imaging using HST/ACS confirms that they possess the same stellar population (Ferguson, 2004a). It seems likely that the northern feature is an extension of the stream, after it has passed very close to the centre of the potential of M31 (Font, 2004; Ibata, 2001).

A second large stellar stream candidate has also been identified with the INT WFC photometry (McConnachie, 2004c). The visible part of this feature

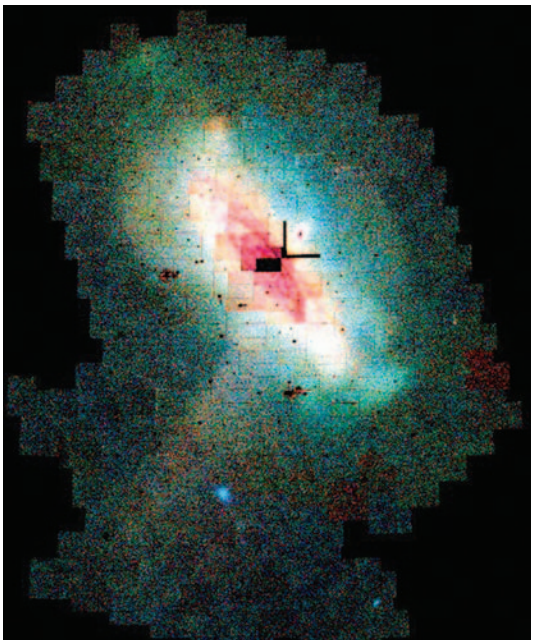

Figure 1. A multi-colour mosaic of the INT WFC survey of M31, involving 165 individual pointings over 40 square degrees of the sky. North is at the top, and East is to the left of this image. Metal poor/young stars are coloured blue, while metal rich/old stars are coloured red. The (colour-dependant) substructure is obvious, and surprising given the pristene nature of the Galactic disk. The dwarf galaxies Andromeda I & III are visible at the bottom left of this figure; the newly discovered dwarf spheroidal, Andromeda IX, is just visible at the top left as a small blue dot. NGC 205 is also visible in this figure, at the right-hand side of the disk.