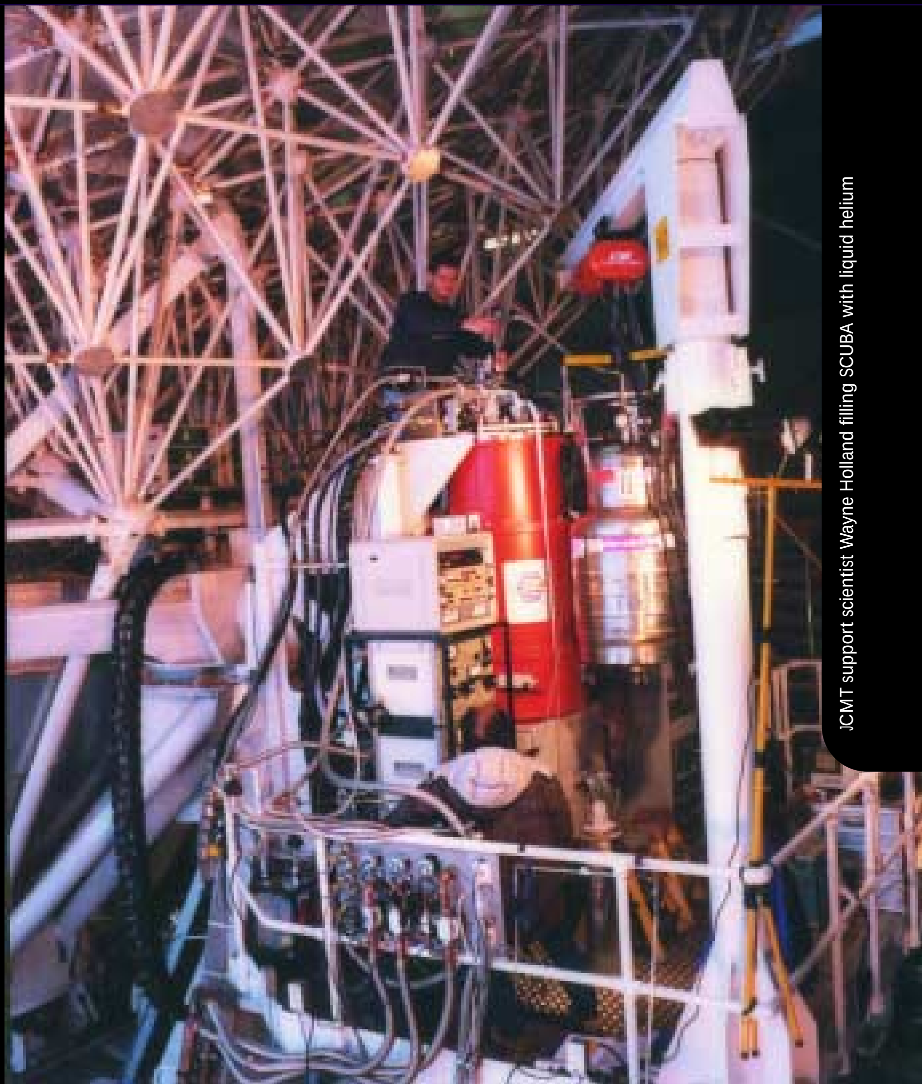
A ground-breaking, UK-built camera has revealed new views of the formation of galaxies, stars and planets



JCMT support scientist Wayne Holland filling SCUBA with liquid helium

SCUBA's

Ian Robson

SCUBA, the Submillimetre Common-User Bolometer Array on the James Clerk Maxwell Telescope in Hawaii, has been an absolutely stunning success. In the four years since its commissioning this remarkable imaging device has not only revolutionised astronomical observations in the submillimetre range but has also provided new insights into a wide range of astrophysical studies. A recent survey by the US-based Space Telescope Science Institute (STScI) revealed that scientific results from SCUBA have been cited almost as often as those from the Hubble Space Telescope (HST), and much more so than those from any other ground-based facility or satellite project. Given that SCUBA is only an instrument and not a telescope – like the twin Kecks, for example – this is an amazing testament to what SCUBA has achieved, and indeed, continues to achieve for the astronomical community.

Here, I will focus on three key areas in which SCUBA has revolutionised astronomy: dust discs around nearby stars; galaxy evolution in the early Universe; and submillimetre polarimetry. A fourth area, wide-field mapping to obtain an unbiased census of star formation in our Galaxy, was described in *Frontiers*, 11, p. 14.

Dusty star discs

The first programmes looking at dusty discs around nearby stars had immediate success, with a number of spectacular images that made huge press headlines, especially for the stars Fomalhaut and Epsilon Eridani. In the UK, the work has been spearheaded by Jane Greaves, Wayne Holland and Bill Dent (now at the UK Astronomy Technology Centre) and the latest image of the dust disc around Fomalhaut at 450 micrometres is shown in Figure 1. At this short submillimetre wavelength, the telescope beam-size is equivalent to a spatial resolution of 50 times the distance of the Earth to the Sun at the distance of Fomalhaut. Figure 2 shows the amazing dust ring around Epsilon Eridani which is only 10 light years away.

Evolution of galaxies

Moving to the other extreme of the Universe, SCUBA observations have helped open up a whole new area of study – that of the evolution of early galaxies. A large UK consortium was able to make a spectacular image of distant galaxies in a section of the sky already revealed by the Hubble Deep Field North (a survey of the distant Universe undertaken at optical wavelengths by the HST). These so-called SCUBA galaxies lie mostly at high redshifts (at least 1.5 – in other words, SCUBA sees them as they were when the Universe was a quarter of its present age). They are extremely difficult to detect at optical or infrared wavelengths, being rich in dust, but are very bright in the submillimetre region. Indeed, it is most likely that these luminous galaxies could account for most, if not all of the submillimetre background radiation which was discovered by the NASA COBE satellite (which detected low-temperature radiation from the early Universe).

To understand the role of these sources in galactic evolution required a much larger sample, however. A number

Figure 1
The dust ring around Fomalhaut at 450 micrometres
The image shows a highly inclined ring, which is both irregular and asymmetrical. Importantly, the inner region towards the star itself is devoid of cold dust, strongly suggesting that it has been swept clear by large planets. The submillimetre emission that connects the two end-lobes in the ring itself shows a distinct bend, which is probably due to an orbiting clump of dust. One possible origin for this is a collision between two planetesimals (small clumps of orbiting planetary matter) in the disc, another is through the gravity of a planet which can couple with the gravity of the dust clump and 'lock' it into a particular orbit. An object the size of Saturn orbiting at about 100 AU from the star could readily explain this clump along with those seen in other similar stars

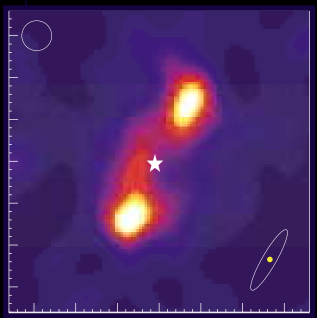


Figure 2
Epsilon-Eridani at 850 micrometres
The white star denotes the position of the star itself surrounded by the emission from cold dust. The arcs and gaps are most likely due to a planetary system, and there is independent evidence from measuring the radial velocity of the star for the presence of at least one giant planet. As Eps Eri is almost the same mass as the Sun but only around 10 to 20 per cent as old, in effect we can examine the early history of formation of our own Solar System!

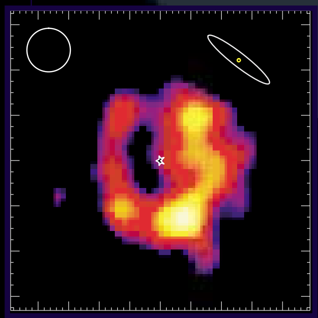
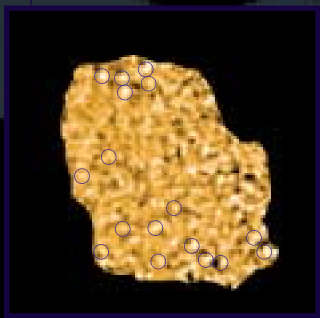
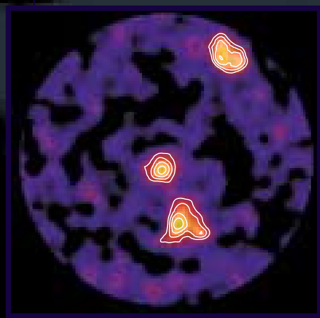


Figure 3
Distant galaxies in a field of about 130 square arcminutes
The brightest sources are encircled. Most interestingly, the density in space of the SCUBA galaxies at a redshift of around 2 suggests that they most probably correspond to the massive ellipticals we see at the present epoch – a fascinating conclusion



James Dunlop (ROE)

Figure 4
Star formation in the early Universe
The SCUBA map shows dust emission at 850 micrometres from the galaxy 4C41.17 (redshift 3.8) and its immediate environment revealing extensive star formation at very early epochs in the Universe



Rob Ivison

amazing success

of SCUBA surveys, mostly UK-driven, were subsequently started. These sampled different areas of the sky at different depths and have been ongoing for the past two years. The results of the most extensive, the UK-led '8 mJy survey', are just now coming out. Figure 3 shows one of these images.

The submillimetre emissions indicated that the cold dust in these galaxies was being heated – but how? Was it due to stars forming from aggregations of dust or to active galactic nuclei (AGN) hidden at the centres of these sources (AGN contain black holes which release massive amounts of energy at all wavelengths). Current evidence suggests it is the former since there is little correlation between the SCUBA sources and X-ray sources detected by X-ray telescopes CHANDRA and XMM-Newton (AGN are one of the main sources of X-rays). It is now clear there was star formation on a huge scale during this early epoch.

Strongly linked with this work is that certain theories of galaxy formation predict that the first galaxies that formed in the early Universe were massive and subsequently evolved into the galaxy clusters we see today. This idea is being tested with SCUBA using AGN as the signposts. A dozen sensitive submillimetre maps of high-redshift AGN indicate that the far-infrared emission in their host galaxies extends out to about 10 arcseconds, which is equivalent to distances of 50 to 200 kiloparsecs across (1 parsec equals 3.262 light years). Maps such as Figure 4 provide a unique insight into how these massive galaxies formed. They reveal substantial star-formation episodes. The earliest stars formed around pre-existing active nuclei at look-back times of about 90 per cent of the age of the Universe, and appear to be spread out on extremely large scales.

This picture is quite different from what we see in nearby galaxies that are merging or colliding, so triggering bursts of star formation in their central regions. The extensive dust emissions revealed by

SCUBA show that, when it comes to star formation, the patchy emissions seen in UV/optical regions from these galaxies represent only the tip of the iceberg, with most or all of the star-forming activity obscured from view.

Magnetic field structures

Turning now to something completely different. In 1998, an instrument for measuring the direction of magnetic fields in sources was added on to SCUBA. This is an important area of study – magnetic fields probably play an important part in star formation. SCUBAPOL provides the first large-scale imaging polarimeter for the submillimetre range, and its use has brought about a wide-range of exciting programmes that have opened up this area. They have studied the magnetic-field structures in Bok globules (small dark clouds of gas and dust which are condensing into stars), proto-stars, star-formation regions, the Galactic Centre, and nearby and active galaxies.

One of the most spectacular results to date comes from Brenda Matthews at McMaster University in Canada. Her map showing the magnetic field structure of the Orion OMC3 star-formation cloud (Figure 5) was possible only because SCUBAPOL, with SCUBA, is able to map magnetic-field orientation across large areas. It is clear that these exciting new results show that the field of submillimetre polarimetry is poised to flourish.

Although flushed with the success of SCUBA, the JCMT is not standing still. A new instrument is already in progress, SCUBA-2. This has just attracted special funding of £4M from the Office of Science and Technology. SCUBA-2 will be a wide-field mapping machine using the first of a new generation of detectors, a monolithic array of transition-edge sensors (TES), the first 'submillimetre CCD'. SCUBA-2 will be delivered to the JCMT in the last quarter of 2005 and will be described in a future article for *Frontiers* by the Project Scientist, Wayne Holland. ✦

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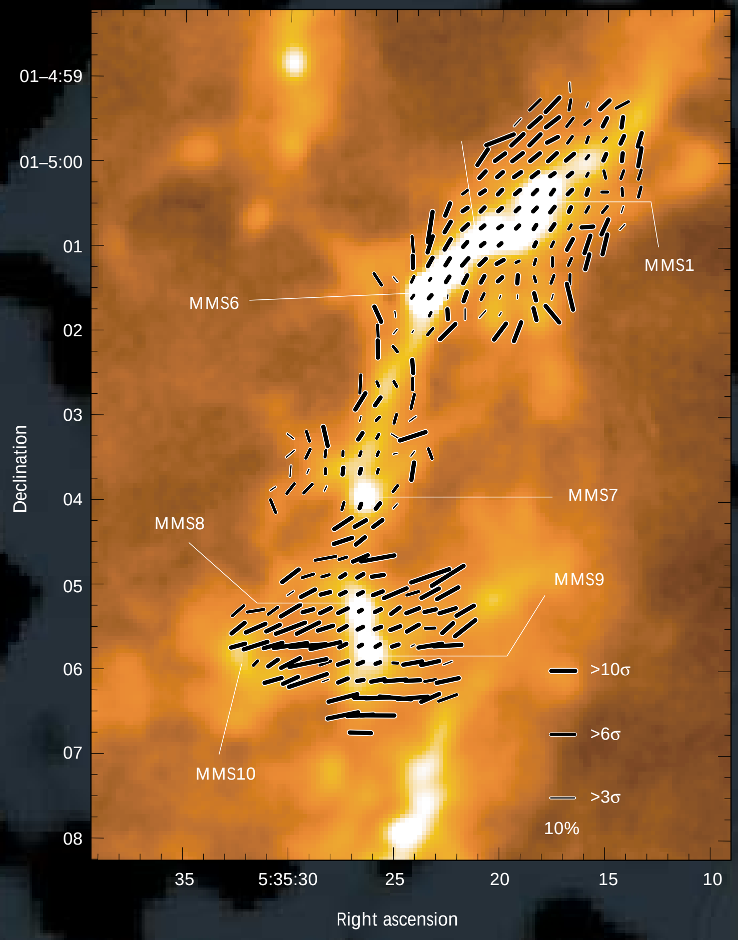

Figure 5
Magnetic measurements in star-forming regions
The Orion Molecular Cloud 3 imaged at 850 micrometres showing that the geometry of the magnetic field is far from simple. The polarisation is smoothly continuous along the cloud's filamentary structure except at the south, where the polarisation vectors become misaligned with the filament axis. Simple models with the magnetic field following the axis cannot explain the field geometry and more complex geometries (such as a helix) are being tested

The new polarimeter on SCUBA for measuring magnetic fields (see above)

A winning partnership

The James Clerk Maxwell Telescope (JCMT) views the sky in the submillimetre region of the spectrum. At these wavelengths, the telescope can resolve objects in the dusty regions in space that would normally be obscured at visible wavelengths. The SCUBA instrument, which has been operating on the JCMT since 1997, is the first of a new generation of submillimetre cameras. It consists of two hexagonal arrays of bolometric detectors, which detect the impinging radiation, at 450 and 850 micrometres, by registering the resulting rise in temperature. SCUBA is incredibly sensitive, being cooled close to absolute zero to minimise stray thermal interference from the environment.

Because the wavelength of radiation is related to the temperature of its source, millimetre measurements can reveal something about cooler objects in space, like interstellar dust – as compared with, say, X-rays, which are emitted by very hot objects such as the centres of active galaxies.