# Probing the Milky Way

**Charlie Walker**, **Ben Shaw**
and colleagues give an overview of how the sensitivity, superb resolution and lack of obscuration in e-MERLIN data is changing what we know about our home galaxy and the lifecycles of its stars.

From star formation to masers to the formation of exoplanets, the capabilities of e-MERLIN are ideally suited to the study of a wide range of important astrophysical processes within our own galaxy. The superb resolution provided by the 217 km extent of the array allows astronomers to study optically obscured regions within the Milky Way in exquisite detail, and the flexibility of the new correlator enables several spectral lines to be probed simultaneously in one observation. Here we highlight some of the ongoing studies trying to understand our home in the universe.

The interstellar medium (ISM) is composed of gas in ionic, atomic and molecular forms, as well as dust and cosmic rays. Stars form within the densest regions of the ISM, so its physics and chemistry play a crucial role in the star-formation process. Young stars are often embedded in very dense and thick molecular clouds, obscuring them at optical and infrared wavelengths. Fortunately, radio waves can penetrate this material. Here we examine e-MERLIN legacy projects and related observations that investigate different aspects of galactic astronomy (see table 1 on page 3.29).

## Low-mass star formation

In the 1980s, it came as a surprise to astronomers that the process of star formation resulted in the ejection of gas from the newly forming star into the surrounding interstellar medium in the form of collimated jets. Until then, it was thought that gas fell exclusively inwards towards the star as it formed. These outward-pointing jets are hot, ionized and produce thermal emission, and can be imaged and studied at radio wavelengths.

It is now thought that stars in the process of formation are surrounded by rotating discs of gas and dust, threaded by magnetic fields that rotate with the disc. Blobs of ionized gas can be trapped in the magnetic fields, lying along the field lines like beads on a wire; they are accelerated and ejected from the disc. At larger distances the magnetic field is wrapped around like a tube and collimates the outflowing gas into jets. The more massive the star is, the faster the jets move away and the more mass is carried away, making more powerful jets. But these powerful jets have shorter lifetimes.

This picture fits observations of the early stages of the life of massive stars. However, the acceleration and collimation mechanisms thought to drive stellar jets are theoretical. These processes take place at small scales, and so high angular resolution is necessary in order to see the action.

While the formation of all types of stars results in jets, low-mass stars (ranging from 0.1 to a few solar masses) are abundant in the galaxy and so make excellent laboratories for understanding the morphology and evolution through time of thermal jets.

> **"In the 1980s, it was a surprise that star formation resulted in collimated jets"**

The e-MERLIN legacy project Morphology and Time Evolution of Thermal Jets Associated with Low Mass Young Stars is targeting these objects, with the aim of testing specific morphological predictions of jet models. The aim is to use e-MERLIN to image the 5 GHz free-free emission from jets from low-mass protostars and compare this with matching-beam Jansky Very Large Array (JVLA) 43 GHz observations tracing the dust from the disc, obtaining information on the scales of the acceleration and collimation processes and on how close to the star ionization begins. This will be the first time that a high-resolution comparison between the dust and free-free emissions will be possible. The goal is improved understanding of the jet–disc relation and of the physics that characterizes low-mass star formation.

The target stars are mostly in the Taurus molecular cloud; at 140 pc distance from the Earth they are the closest stars to us that are in the process of forming. Recent observations made with ALMA and the JVLA, providing similar angular resolution to e-MERLIN but at shorter wavelengths, indicate that in the inner 10 au around a young star there is a blend of emission from the dust in the protoplanetary disc and from the ionized gas in the jet. As a result, observations from all three instruments are necessary in order to distinguish between the different emission mechanisms. This inner region is key to our understanding of planet formation because planets and exoplanets are thought to form there. Results from early observations on this project suggest that, while acceleration happens very close to the star, the collimation takes place relatively far away (Rodríguez *et al.* 2008).

## Massive stars

Despite being less numerous, massive stars (>8 solar masses) have a wider influence than any other type of star because their strong stellar winds, high ionizing fluxes and ultimate supernova detonations have a profound effect on the dynamical and chemical evolution of galaxies at both low and high redshifts.

These stars are born as O and B stars with effective temperatures of between about 25 000 and 50 000 K, and luminosities in the range of 20 000 to 1 million times the solar luminosity. They are rare and short-lived; observing them in the act of forming is a challenge because this phase lasts only about 100 000 years.

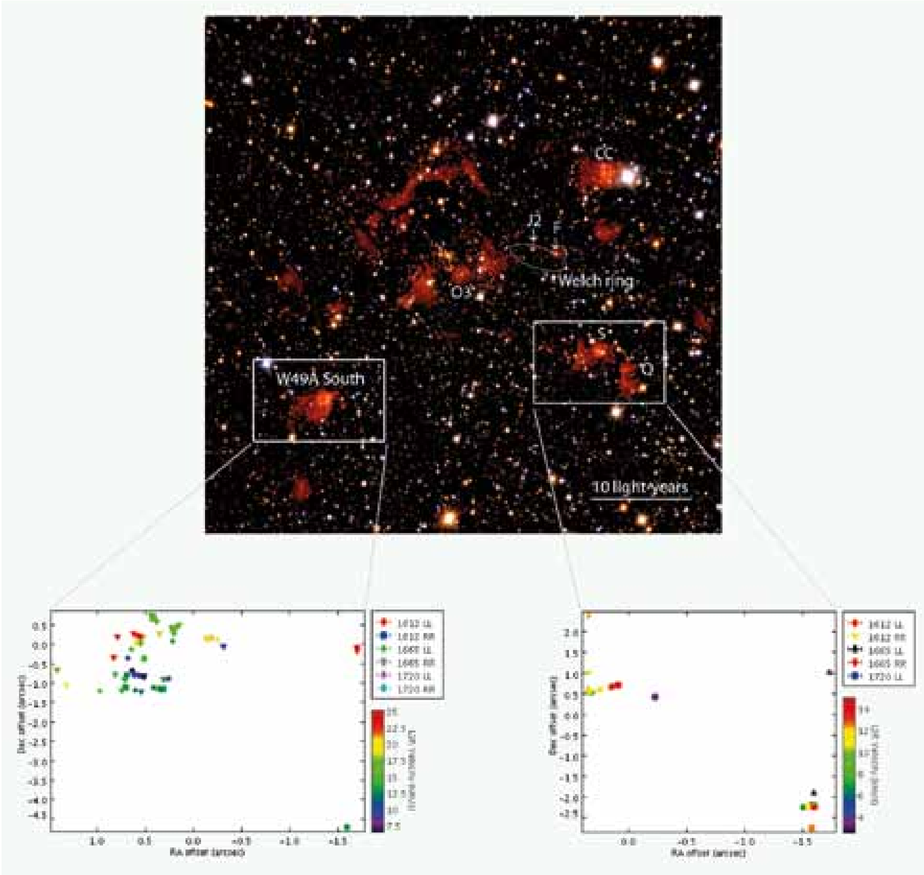
On the main sequence they burn hydrogen in their cores, and experience mass loss throughout their evolution, ejecting large amounts of material into the immediate surroundings. These stars have powerful effects on their surroundings; the UV radiation from massive stars can destroy the protoplanetary discs of low-mass stars born in clusters. But they also provide a useful tracer of gas in other galaxies; H II regions ionized by massive stars are fundamental in extragalactic astronomy to determine current star-formation rates and light-element abundances. The energy released by luminous OB stars is a driving force in the development of large and small-scale structure in the interstellar medium. Furthermore, the energy they provide through photoionization, winds and supernova explosions can result in expanding shells and super-shells within galaxies and, in extreme cases, galactic winds. The metals returned to the interstellar and intergalactic media are important for the cooling efficiency of hot gas and constitute part of the feedback loop in the chemical evolution of galaxies. On an even grander scale, massive stars were probably significant during cosmic reionization at the end of the "dark ages".

### Masers and massive-star formation

One probe of the star-formation process is the cosmic maser, the microwave analogue of the laser. Maser emission takes place when there is a high enough density of a species, and where a critical population of the ions are excited above their ground state (a process called pumping), perhaps as a result of collisions or through external radiation. In these conditions, absorption of a photon induces enhanced emission, resulting in the amplified maser emission, characterized by unusually narrow line widths, anomalous line ratios and much higher equivalent temperatures resulting from the amplified radiation. As a result of requiring very specific conditions, masers are unique and important tools and are valuable signposts for active star formation and regions of extremely dense gas. Studying the spatial distribution of the masers, the velocity gradient across the region, the polarization of the lines and their velocity profiles, can help understand the physical processes and gas motions within important star-forming regions.

The OH radical produces one of the most abundant and easily detectable masers, usually found in regions of active star formation near young stellar objects. The most easily detectable transitions of the OH maser are from the ground-state main lines at 1665 and 1667 MHz, and the excited-state satellite lines at 1612 and 1720 MHz. The measured properties of these spectral lines, such as the line ratios, widths, redshifts and polarization, provide detailed information about physical conditions in the circumstellar gas. However, in order to study the processes on small scales inside molecular clouds we need high resolution, and that requires interferometry – as applied here to observations of the W49 giant molecular cloud.

This giant molecular cloud lies 11 kpc away in the constellation of Aquila and comprises two radio sources: the giant active star-forming region W49A, and the supernova remnant W49B. W49A is the most luminous star-forming complex in our galaxy, outside the galactic centre. It spreads over more than 50 pc, with a mass of more than 100 solar masses and contains many luminous stellar clusters.




**1** The star-forming complex W49A, showing multiple OH maser sites across each subregion, and velocity gradients across each collection of maser spots. The colour coding represents the velocity of each maser feature, relative to the local standard of rest. (K Asanok [Khon Kaen University, Thailand])

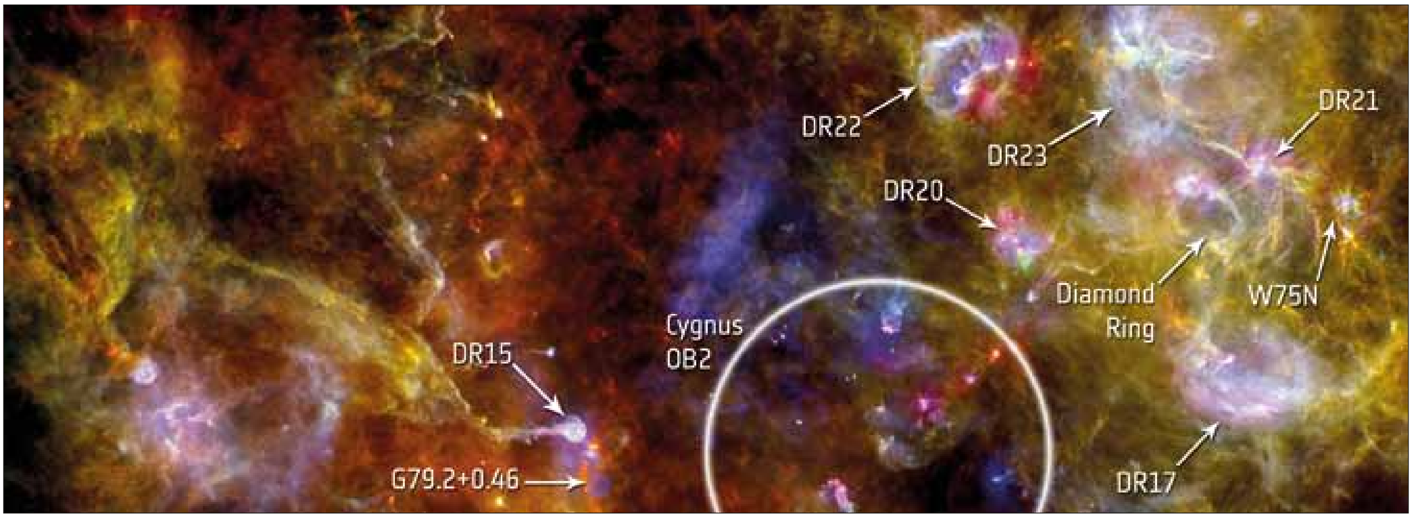
This region lies in the galactic plane at a distance of $11.11^{+0.79}_{-0.69}$ kpc and contains ~40 ultra-compact H II regions associated with a minimum of 40 OB stars (earlier than B3). Inside this complex there are several infrared peaks associated with ultra-compact H II regions where stars are forming. Radio observations with e-MERLIN resolve these regions and show OH maser features distributed over a region of more than ~10 square-arcsec towards two of these regions (Asanok *et al.* 2015). Figure 1 shows the locations of some of the prominent maser clumps in the W49A region.

### Dense star-forming clusters

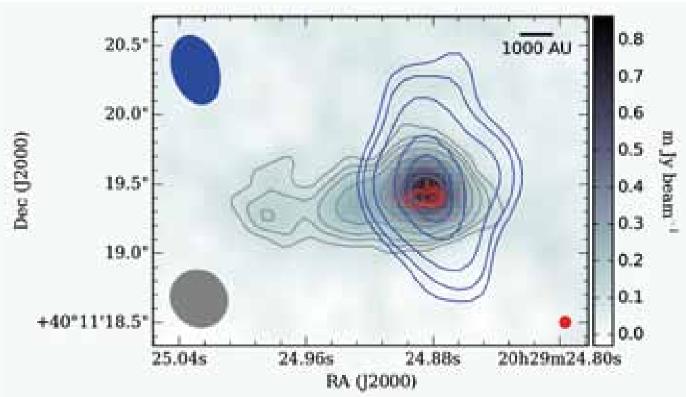
Cygnus-X is one of the richest regions of star formation in the galaxy, covering a patch of sky nearly 10° across (figure 2). COBRaS, the Cyg OB2 Radio Survey, is an e-MERLIN legacy project designed to perform a deep radio survey of one of the most massive star clusters in the galaxy, Cygnus OB2, focusing on the centre of the complex.

Cyg OB2 is not only very dense but also diverse, with more than 2500 OB stars and ~100 O-type stars, making it a uniquely important laboratory for studying the collective and individual properties of massive stars. At a distance of just 1.45 kpc, it is also one of the closest young massive stellar clusters and offers direct comparison not only to massive clusters in general, but also to young globular clusters and super star clusters found in galaxies with high rates of star formation. Located behind the Great Cygnus Rift, Cyg OB2 is heavily obscured at optical wavelengths, but it is an ideal target for radio studies. The very high sensitivity of the e-MERLIN survey provides a substantial improvement on previous radio work on this cluster, and the wide-band capabilities of the new system enable a determination of not only the flux, but the spectral index as well, allowing observers to distinguish between thermal and non-thermal radiation.

One of the key aims of the COBRaS project is to determine how and how quickly the massive OB stars in Cyg OB2 lose their mass, a parameter that determines their evolution and ultimate fate. Radiation-driven stellar winds are considered to be the principal agent of mass loss. But current models of the mechanisms have come under challenge from recent observational results (Fullerton *et al.* 2006), that suggest that clumping in the winds can limit the mass-loss rate, highlighting the need to determine the extent of such structure within the stellar wind. The free-free radio emission produced in the stellar wind of OB stars is highly sensitive to clumping, making it a useful diagnostic. The COBRaS project will observe the region at 5 GHz with the highest sensitivity and resolution;




**2** The Cygnus-X region as seen in the infrared. The COBRaS project is performing a deep radio survey of Cygnus OB2, one of the most massive star clusters in the galaxy. (ESA/PACS/SPIRE/M Hennemann & F Motte, Laboratoire AIM Paris-Saclay, CEA/Irfu – CNRS/INSU – Univ. Paris Diderot, France)




**3** Above: e-MERLIN 6.5 GHz emission (red contours) at 0.080″ resolution from the massive young stellar object GL 2591 (Johnston *et al.* in prep). A 0.4″ resolution 8 GHz VLA image is shown in grey contours (Johnston *et al.* 2013). Blue contours show 0.4″ resolution 203 GHz emission (Wang *et al.* 2012) that mostly traces the dusty disc perpendicular to the radio jet as well as hints of jet emission. Right: The Gemini view of the same region. The resolution of this NIRI (Near-Infrared Imager) image is 0.4 arcsec. (Gemini Observatory/AURA)

1.4 GHz observations have already enabled determination of mass-loss rate limits, providing significant constraints for a number of massive stars within Cyg OB2 (Morford 2014, Morford *et al.* 2016 in prep.).

The other main aim of COBRaS is to study binary stars and the synchrotron emission caused by stationary shocks created where the winds from the two stars collide. The wide bandwidth and frequency coverage of e-MERLIN will enable the detection of these systems via the steep spectral index of the non-thermal synchrotron emission. The COBRaS data will allow us to improve our understanding of the physics involved in particle acceleration within shocks by studying in detail the individual binary systems. These observations will also enable us to study statistically the colliding-wind phenomenon and better understand its dependence on stellar and binary parameters.

In addition to observing the known binary systems within Cyg OB2, COBRaS is expected to detect a number of previously unidentified or completely unknown binary systems within the region and the L-band observations have already provided a number of potential candidates.

## Feedback processes

Another large legacy programme is Feedback Processess in Massive Star Formation. Massive-star formation is modelled as an accretion disc with, along its rotation axis, ionized jets ejected at several hundred km s$^{-1}$. This picture is similar to that in low-mass young stellar objects where the jets are thought to be driven by magnetic forces. Traditionally, massive stars have not been considered magnetically active, but dominated by radiation pressure forces. A relatively new theory is that when they are forming and accreting at high rates, they can swell up to be more like red giants. They could, therefore, have convection zones and associated dynamos; evidence of magnetically driven jets may teach us a lot about the nature of the new star itself.

Previous satellite-based surveys of the galactic plane at mid-IR wavelengths found many sources with the characteristics of massive young stellar objects, but it took 10 years of ground-based follow-up to sort out the genuine targets from others that masquerade as such. Multi-wavelength observations allow rigorous sample selection. This sample selects high mid-IR luminosity, but cool colours, indicating massive but young sources. Warmer objects (but still sub-mJy radio sources), are more evolved but have not yet ionized their surroundings. The presence of a 6 GHz methanol maser also guarantees massive star formation. The targets chosen for this survey have a range of mass and infrared colours that are believed to be proxies for stellar mass and age (Rathborne *et al.* 2005). In this way the team will be able to track how the feedback characteristics change over time. For instance, are the young objects swollen and magnetic with bipolar winds (Purser *et al.* 2016), like lower mass stars, while the more evolved ones have the disc-like winds driven by radiation pressure?

e-MERLIN provides the highest resolution while remaining sensitive enough to be able to detect the thermal bremsstrahlung radiation that these jets and winds emit. The survey has begun and the team plans to observe 75 targets in all. One early result concerns the jet in GL 2591, a massive young stellar object that is one of the most luminous targets (figure 3). VLA data had previously shown that this object has a jet; e-MERLIN data show details at five times higher resolution, allowing the researchers to examine the base of the jet where it is driven and collimated.

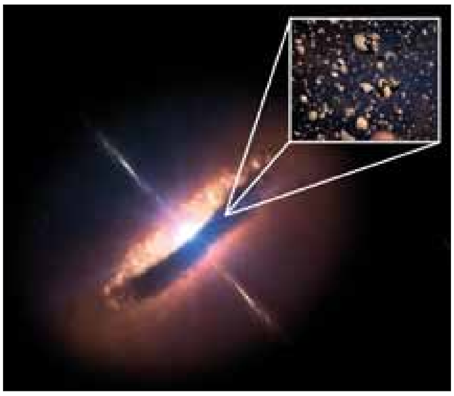
The sample spans a range of evolutionary stages from sources deeply embedded in infrared-dark clouds to massive young stellar objects that are bright in the mid-IR. Deep continuum imaging will determine when magnetically driven jets turn on, when they give way to radiatively driven disc winds and over what mass range they operate. The survey will also examine how the ionizing radiation from the young star affects its surroundings. The stage at which the ionizing radiation first breaks out into a hyper-compact H II region will determine its later density distribution and the physical processes that shape the gas. The team will also map the 3D magnetic field structure in some sources using methanol and excited OH maser polarization. Together these data will test both the physics of the feedback mechanisms and evolutionary models of massive-star formation.

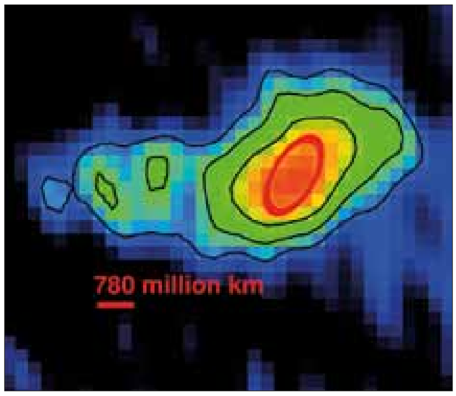
## Building planets

Once young stars begin to shine, their stellar winds start to clear away the remnants of the surrounding cloud of gas and dust from which they formed. Lingering material in circumstellar discs eventually leads to the formation of planetary systems.

Imaging faint Earth-like planets around much brighter Sun-like stars is difficult, but an enticing, if distant, prospect. In order to better understand the development of our own solar system and the prospects for life in the wider universe, it is important to understand how planets form, whether terrestrial planets are common and if it is likely that suitable conditions for life exist beyond the Earth. Since the 1990s, astronomers have found stellar discs of gas and dust, and tracked almost 2000 fully formed planets, but the intermediate stages of planetary formation are harder to detect.

It seems that Earth-like planets form as small orbiting solid particles – dust – bind together, building rocks that collide and ultimately merge to form planetary cores. Like all warm objects, the pebbles emit radiation as heat, detectable at infrared and radio wavelengths. Detecting these faint signals requires both good sensitivity and high resolution, making e-MERLIN ideal.






**4** Left: An artist's impression of the belt of centimetre-sized rocks – pebbles – in orbit around the star DG Tauri. The inset is a close-up view of a section of the belt. (J Ilee, adapted from original work by ESO/L Calçada/M Kornmesser, ALMA [ESO/NAOJ/NRAO]/L Calçada [ESO]).
Right: An e-MERLIN map of the star DG Tauri. The yellow and red areas show what is thought to be a ring of pebble-sized clumps in orbit around the star. (J Greaves/A Richards/JCBA)

The PEBBLeS project (Planet Earth Building-Blocks, a legacy e-MERLIN survey) is an ultra-deep continuum survey of the circumstellar discs. PEBBLeS homes in on discs predicted to be the most conducive to planet formation: those around Sun-like stars with long lifetimes where planets could form in the habitable zone and survive long enough for life to evolve. Imaging the thermal emission from pebble-sized dust grains will show where and when planet-core growth is proceeding, and identify accreting protoplanets. The aim is to determine which types of young star are forming pebbles and so have the best prospects for making planets.

**"Observations at 5 GHz are sensitive to particles a few centimetres across"**

Observations at 5 GHz are providing the required resolution while remaining sensitive to particles a few centimetres across. Early observations of the star DG Tauri, just 2.5 million years old and 450 light years away, showed a faint glow characteristic of rocks in orbit around the newly formed star (figure 4). The resolution of e-MERLIN at 5 GHz allowed the team to image a region as small as the orbit of Jupiter around the Sun, finding a belt of pebbles strung along an orbit like Jupiter's – just where they are needed if a planet is to grow in the next few million years. Having an accurate idea of the location and amount of the centimetre-sized material in the disc will bring us closer to a consistent picture of how planets form – and answer questions about the origin of planet Earth.

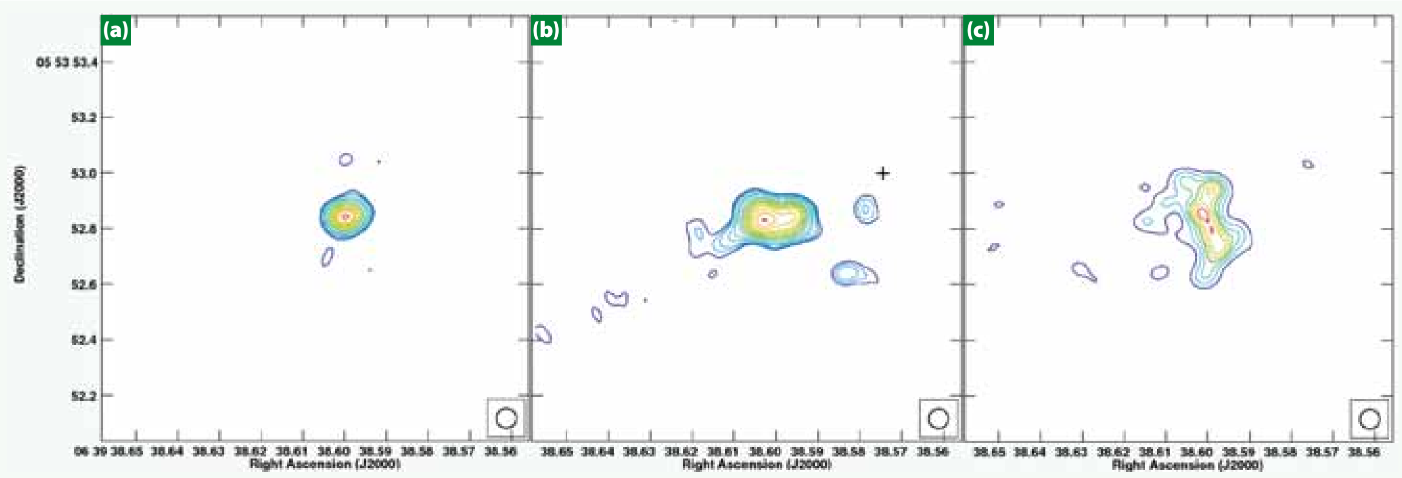
## Radio transients

Studies of the stellar life-cycle are not restricted to large surveys, of course, and many individual objects have been observed with the upgraded system. One such source is V959 Mon (also known as Nova Mon 2012), first detected by the Fermi Large Area Telescope in June 2012 as a gamma-ray transient. Later optical observations showed that this gamma-ray emission came from a classical nova explosion (Cheung *et al.* 2012), a binary star system consisting of a white dwarf and a Sun-like star undergoing sporadic outbursts.

Multi-frequency observations of V959 Mon with the JVLA between June and September 2012 revealed dramatic brightening and a spectrum that steepened with increasing frequency (Chomiuk *et al.* 2014). V959 Mon exhibits several traits that are contrary to the standard models of mass ejection from novae, for example the emission of gamma-rays and its aspherical morphology, observed by other telescopes including the JVLA and the EVN.

A model proposed by Chomiuk *et al.* (2014) suggests ejecta that consist of two components moving in perpendicular directions; a slower-moving equatorial component driven by orbital energy transferred from the binary system, and a faster-moving component emanating primarily from the poles of the white dwarf and driven by winds on the white dwarf surface. In radio data, the faster component would dominate images first, before becoming optically thin and leaving the slower equatorial component visible.

Early e-MERLIN observations of V959 Mon appear to show an east–west elongation in the ejecta morphology (figures 5a and 5b). Subsequent observations show that the ejecta are now elongated in the north–south direction (figure 5c). V959 Mon's angle of inclination is 82° (Ribeiro *et al.* 2013), meaning that the orbital plane of the binary system is aligned almost north–south in the plane of the sky. The change observed in orientation of V959 Mon's morphology is in agreement with the predictions of Chomiuk *et al.* (2014), suggesting that the data show both the fast equatorial jet – running east–west – and the slower emission from the disc. To date there




**5** Evolution of V959 Mon at 5 GHz. Initially, the ejecta from the outburst appear to be elongated east–west (a, September 2012) and (b, November 2012), but later appear to align north–south (c, October 2013). (F Healy [JBCA, University of Manchester])

are seven epochs of e-MERLIN observations of V959 Mon; these high-resolution data can assist us in further understanding the mechanisms of mass ejection.

## X-ray binaries

When one star in a binary evolves faster than the other, the result can be a main sequence star in orbit around a more exotic evolved companion. This is the case for V404 Cygni (V404 Cyg), which on 15 June 2015 began to flare spectacularly across the whole electromagnetic spectrum. V404 Cygni was known to astronomers in the 18th century as a variable star and until the late 20th century it was considered to be a nova, but an outburst in 1989 showed that it is a low-mass X-ray binary, consisting of a black hole consuming matter from its Sun-like companion star. Observations of V404 Cyg in a quiescent state found that the compact object was a black hole 12 times more massive than the Sun, with a companion star about half the mass of the Sun.

On 15 June 2015, the Swift space telescope detected a burst of X-ray emission from V404 Cyg, triggering an intense observing campaign. Observations during the first few days of the outburst revealed several flares with increasing peak brightness, and oscillations in the intensity of the radio emission on timescales as short as one hour. These oscillations are thought to arise from the inner accretion disc, as it repeatedly ejects matter and refills.

Simultaneous optical and radio data showed that some flares appear correlated: optical emission arises from the base of a jet, where accreted matter is expelled in a collimated outflow, while the radio emission comes from further along the jet. The time lag between the signals suggests that the radio-emitting region lies a few thousand light seconds from the black hole.

Many radio flares were seen over the 30-day outburst, probably associated with relativistic ejections of the accreted matter. Early e-MERLIN observations, made as part of a larger campaign, provided vital data on the 2015 outburst at radio wavelengths. VLBI data taken during the outburst revealed blobs of plasma ejected by V404 Cyg, moving at speeds close to that of light. The directions of motion of the blobs were expected to be aligned with the spin axis of the black hole, but the results hint at blobs moving at two different angles, possibly due to precession of the black hole spin. The most likely explanation for these periodic outbursts is that material from the companion star is piling up in a disc around the black hole until a saturation point is reached, at which point the material is fed to the black hole rapidly, giving rise to an outburst.

After the outburst, the research focus has moved on to analysing and interpreting the vast collection of multiwavelength data, and modelling the flares in order to extract the interesting physics from the outburst data. The aim is to derive the energetics of the outburst and, for the first time, directly compare the jets launched by stellar-mass black holes in our own galaxy with those from supermassive black holes in much more distant and powerful galaxies.

## Pulsars

At the other end of the life cycle of massive stars are core-collapse supernova explosions, producing neutron stars and stellar-mass black holes. The final galactic legacy programme, the e-MERLIN Pulsar Interferometry Project, will examine the physics of neutron-star formation during supernovae, in order to improve understanding of the structure of our galaxy. The programme aims to more than double the number of pulsars known with accurate distance and velocity measurements. Neutron stars have the highest velocities of any class of stars; a "kick" during the supernova that forms them appears responsible. This programme will use model-independent velocities to constrain this mechanism. Such strong constraints are essential for probing the laws of physics under the extreme conditions of supernova core-collapse.

Pulsars with known distance measurements provide essential calibration points for galactic electron density structure models, in turn improving distance estimates for pulsars for which there is no accurate astrometric data. Combined with observations of thermal radiation from the pulsar surface, distance measurements will constrain neutron-star sizes with important implications for the neutron-star equations of state. Knowing the proper motions also allows us to determine the birth locations of young pulsars, and potentially associate them with the supernova remnants in which they were born and again allow us to study the physics of their birth. Moreover, once we know the distance to a pulsar, improved tests of theories of gravity and/or measuring the masses of neutron stars in binaries also become possible. ●

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