The e-MERLIN Cyg OB2 Radio Survey (COBRaS): Massive and young stars in the Galaxy

Abstract The e-MERLIN Cyg OB2 Radio Survey (COBRaS) is designed to exploit e-MERLIN's enhanced capabilities to conduct uniquely probing, targeted deep-field mapping of the tremendously rich Cyg OB2 association in our Galaxy. The project aims to deliver the most detailed radio census for the most massive OB association in the northern hemisphere, offering direct comparison to not only massive clusters in general, but also young globular clusters and super star clusters. With the COBRaS Legacy project we will assemble a uniform dataset of lasting value that is critical for advancing our understanding of current astrophysical problems in the inter-related core themes of (i) mass loss and evolution of massive stars, (ii) the formation, dynamics and content of massive OB associations, (iii) the frequency of massive binaries and the incidence of non-thermal radiation, and (iv) ongoing and triggered star formation.

Based on a total request of 900 hours (primarily comprising $\sim$100 pointings at 5 GHz and $\sim$20 pointings at 1.6 GHz), we estimate that at least 10^3 sources will be detected in our survey. The substantial COBRaS dataset will be powerfully combined with other multi-waveband surveys of the Cygnus X region, both current (IPHAS, Spitzer, and Chandra) and in future programmes (Herschel and JWST). This project will therefore not only yield substantial results for the key science areas identified above, but it will also provide new perspectives for numerous additional archival studies in stellar and extragalactic astrophysics. The COBRaS project will thus yield a very valuable Legacy dataset for the wider community.

1. List of team members

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2. Legacy Science Case

Our goal is to exploit the high-resolution capability and tremendous sensitivity of e-MERLIN to assemble the most substantial radio datasets of an undoubtedly spectacular region of massive stars in our Galaxy. Several factors combine to make the Cyg OB2 association a uniquely important laboratory for studying the collective and individual properties of massive stars. The datasets will be used to significantly advance solutions to current fundamental problems in (i) the mass loss and evolution process in massive stars, (ii) the kinematics and formation of massive clusters, (iii) massive binary frequency and particle acceleration in colliding-wind binaries, and (iv) triggered star formation.

The Cygnus X region hosts five OB associations, numerous young open clusters, tens of compact H II regions and star formation regions, a supernova remnant, and a superbubble blown by the collected stellar winds of the massive stars (Knödlseder 2004, Trapero et al. 1998). At the core of Cygnus X is the Cyg OB2 association. It is relatively close by (at between 1.2-1.8 kpc). Cyg OB2 is a young massive cluster, heavily obscured (as is the whole Cygnus X region), and located behind the Great Cygnus Rift. There is large and non-uniform visual extinction ranging from 4 to 10 mag (Knödlseder 2000), thus making the association ideally studied at radio wavelengths. Knödlseder (2000) showed Cyg OB2 to contain 120 ± 20 O-type stars and 2600 ± 400 OB-type stars. With a total cluster mass estimated to be $(4-10) \times 10^4 M_\odot$, Cyg OB2 can be considered more as a young globular cluster than an open OB association, similar to such clusters in the LMC (Reddish et al. 1966, Fischer et al. 1992). The estimated age of the cluster is $\sim 2{-}3$ Myr (Albacete Colombo et al. 2007). Cyg OB2 is not only very rich in stellar density but also in its diversity. Besides the numerous O and B stars, it contains Be stars, many Young Stellar Objects (YSOs), two known Wolf-Rayet stars (WR 145, WR 146), a candidate LBV (G79.29+0.46), a red supergiant (IRC+40 427), a B[e] star (MWC 349), H II regions with groups of massive stars around them (DR 15, DR 18) and a very-high energy γ-ray source (TeV J2032+4130). All these objects can be expected to emit detectable radio radiation. Many more examples of these types of objects – and other types – will be found by a deep integration using e-MERLIN.

We propose mapping a considerable part of Cyg OB2 at 5 GHz, going to a depth of ~ 3 μJy (1-sigma), plus additional pointings at 1.6 GHz. These legacy data will be of genuine lasting value, with a substantial and diverse science impact. The investment of a substantial amount of e-MERLIN observing time to this young massive star cluster is important as it is one of only a few examples known in our Galaxy (Hanson 2003). As Cyg OB2 is a smaller version of the super star clusters (SSCs) seen in e.g. M82 (Lipscy & Plavchan 2004), it can therefore serve as a Rosetta Stone to help interpret the information from these much more distant clusters.

The COBRaS legacy project is designed to deliver substantial advances in our understanding of Cyg OB2's stellar content, ranging from the most massive stars in their various stages of evolution to low mass stars in their pre-main-sequence (PMS) phase. We seek to provide information about the physical mechanisms working in these objects and the much needed input for modelling work in stellar and galactic chemical evolution.

The proposed e-MERLIN observations will provide pivotal inputs for studies of massive stars, their stellar winds and their evolution from star formation to supernova. They will give information about binary frequency and orbital properties, interaction with the interstellar medium, the initial mass function and stellar nucleosynthesis, and high-energy γ-ray emission. The database will also lead to a better understanding of the evolution of low-mass stars. The project will advance our knowledge of the fundamental properties of the cluster in which massive and less massive stars form.

We divide below the discussion on the planned science return into four inter-related core themes which are of direct interest to our team (though there are clear overlaps between the different topics). In addition, the COBRaS project will undoubtedly deliver data relevant to numerous science areas that extend beyond our core interests, including the detection of a large and diverse range of foreground objects.

2.1. Massive stars: Mass loss, clumping and evolution

The e-MERLIN deep-field mapping of CygOB2 that we propose here is designed to resolve the current very serious uncertainties in the mass loss and energy feedback processes of massive stars. Recent results have strongly challenged the current model of mass loss via stellar winds, with the enormous consequence that currently accepted mass-loss rates of luminous massive stars may be too high by an order-of-magnitude or more. There is the highest urgency to robustly investigate this discordance since it has far reaching consequences for the evolution and fate of massive stars (which is largely determined by mass loss) and for galactic chemical evolution (where mass loss drives chemical and mechanical feedback on the interstellar medium).

Massive stars have a significant influence in many areas of astrophysics. They are major contributors in galactic evolution as they return prodigious amounts of mass, momentum and energy to the interstellar medium (ISM). This happens during the various stages of stellar evolution and, most spectacularly, when these stars explode as a supernova. The material returned to the ISM is chemically enriched by the nuclear processes in the star. The momentum and energy deposition is important for the ionization, heating, turbulence and mixing of the ISM. In this way, massive stars profoundly affect the star- and planet-formation process. They also generate most of the ultraviolet ionizing radiation in the Galaxy. They are sites of cosmic-ray acceleration and have been proposed as an explanation for very-high energy γ-ray observations. Their death as a supernova can explain the observed long-duration γ-ray bursts. The fact that they reside in clusters gives rise to additional interesting phenomena, such as wind-wind collisions, superbubbles and runaway stars. Massive stars also played an important role in the evolution of the Universe, as they must contribute in the reionization epoch.

In view of their undoubted importance, it is then critical to investigate current serious uncertainties in our knowledge of massive stars. The applicants recent work (e.g. Fig. 1) has been pivotal in the current wide recognition that one of the most important issues is the significant discordance in the extent of mass loss occurring via *clumped and/or porous* radiation-driven winds. The mass-loss rates of massive stars are now in question at the *order-of-magnitude* level, and not just a few % (see e.g. Prinja, Massa & Searle, 2005; Fullerton, Massa & Prinja, 2006; Puls et al. 2006).

The mass-loss uncertainty (and wind porosity) has profound implications for broad astrophysical domains, including stellar evolution and the mass-loss process across the H-R diagram, and the injection of enriched gas into the ISM: mass must be shed to produce Wolf-Rayet (WR) stars and neutron stars. Until now, this mass loss has been attributed to stellar winds. However, if these mass-loss rates are as small as the spectroscopic observations indicate, then we may be forced to appeal to episodic mass loss, perhaps through numerous luminous blue variable stages (e.g., Smith & Owocki 2006). If this scenario is correct, then the nature of the energy and enriched gas injected into the ISM may be quite different.

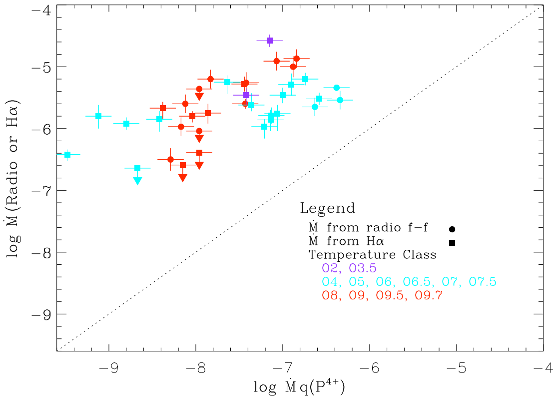

Fig. 1. *There is a substantial current discrepancy between mass-loss rates derived from 'reliable' UV (P^{4+}), Hα and radio (ρ^2) methods. These crucial differences can only be reconciled by a rigorous investigation of wind clumping (e.g. Fullerton, Massa & Prinja 2006).*

OB stars emit radio radiation through (thermal) free-free emission, due to electron-ion interactions in their ionized wind. The considerable advantage of using free-free radio fluxes for determining mass loss for massive stars is that, unlike Hα and UV, the emission arises at large radii in the stellar wind, where the terminal velocity will have been reached. The interpretation of the radio fluxes is more straightforward therefore and is not strongly dependent on details of the velocity law, ionization conditions, inner velocity field, or the photospheric profile. However, the greater geometric region and density squared dependence of the free-free flux makes the radio observations extremely sensitive to clumping in the wind. Radio observations can be used to constrain clumping, and by comparing them with observations in other spectral regions, including near-IR, mm and Hα, we can determine the run of the clumping factor as a function of the geometrical region in the wind (e.g. Blomme et al. 2002, 2003, Puls et al. 2006). Multi-waveband datasets of Cyg OB2 are already available to the project, including the contemporaneous Hα and near-IR (Br-α) spectra from the Cygnus radial velocity survey (Kiminki & Kobulnicky; Table 2). We also anticipate follow-up SCUBA-2 data and that longer waveband IR data will be part of a Herschel proposal.

Based on 2MASS data, Knödlseder (2000) estimates that Cyg OB2 contains 120 ± 20 O-type stars and 2600 ± 400 OB-type stars. A number of the O-type stars have been identified (or candidates have been proposed) through the work of Massey & Thompson (1991), Comeron et al. (2002), Kiminki et al. (2007), but clearly not all O stars in Cyg OB2 are currently known. The spectral types of these O stars cover all ranges, including one of the rare O3 If* (Walborn 1973). Some early-type B supergiants are also present, suggesting that the star formation was not strictly coeval (Massey & Thompson 1991). The tremendous capability of e-MERLIN at centimetre wavelengths makes it the premier international facility for studying massive star outflows and our COBRaS Legacy project will ultimately increase the number of OB stars detected in this cluster by a factor of ∼50.

Our e-MERLIN observations will thus substantially permit us to (i) understand the magnitude of wind clumping and how it changes as a function of radial distance from the star, thus providing reliable estimates of mass-loss rate, (ii) investigate for the first time how clumping (or volume filling factor) changes as a function of fundamental stellar parameters such as temperature, luminosity, rotation velocity and so on. It is critical to discover whether clumping is different between early type and late type giants and supergiants. This will provide powerful constraints on physical models for the origins of clumping. The COBRaS project will yield radio mass-loss rates for low luminosity stars for the first time and thus directly impact on whether clumping is stronger in low mass-loss rate stars; this is an area where the wind theory is currently poorly understood. Only an extensive and deep survey of Galactic stars is able to provide the requisite clumping diagnostics over a wide range of spectral types.

We stress that significant progress can be made with e-MERLIN *point source detections*, and spatial resolution of the wind is *not* a requisite. Snapshot detection projects are an *essential* part of the e-MERLIN science case. We will exploit the huge extension in uv-coverage afforded by the substantial increase in bandwidth that e-MERLIN will have. It is this innovation that will allow e-MERLIN to operate so effectively in snapshot mode. High S/N e-MERLIN observations will additionally enable us to uniquely secure *temporal* radio fluxes for strategically selected targets, over timescales of days. These 'time-series' will permit us to take the next critical step in unravelling the dominant *geometric* nature of the wind structure i.e. are there lots of small clumps or more spatially coherent large-scale structures? The temporal results will be critical for a physically-based treatment of clumping in *ab initio* stellar atmosphere models (e.g. CMFGEN, FASTWIND), which predict continuum fluxes and spectral line profiles. e-MERLIN will also provide higher quality imaging capabilities, which match the ∼ 50 mas angular scales marked by the radio 'photospheres' of massive stars. We intend therefore to also attempt spatial resolution of the brightest targets, to provide 'direct' evidence of large-scale wind structures. Our mosaics of selected regions of Cyg OB2 (see Fig. 2) will also enable us to resolve the winds of massive stars at later stages of evolution, including Luminous Blue Variables (LBVs) and red supergiants.

2.2. Cluster dynamics

Another key goal of our proposal is to use the high spatial resolution offered by e-MERLIN to obtain milliarcsec accuracy astrometric observations of the radio stars within Cyg OB2 at multiple epochs, in order to determine their proper motions. As part of our consortium we have an ongoing program of high resolution spectroscopic observations of the massive stellar populations within Cyg OB2 to identify and characterise massive binaries, which provide radial velocity measurements of comparable accuracy; taken together these complementary datasets will allow a full 3 dimensional picture of the kinematics of Cyg OB2 to be constructed. We emphasise that this is the first time this has been attempted for any massive cluster, and will address a number of scientific goals.

The initial science driver of this facet of the COBRaS Legacy program is to constrain the basic parameters of Cyg OB2. Specifically, the kinematics of the OB stars will enable us to identify co-moving bona fide members of the complex and hence exclude interlopers. From this we will be able to determine the physical size of the complex and also any subgroupings within it (see below). Moreover an accurate census of the OB stars - in conjunction with our spectroscopic binary survey - will allow the most accurate determination of the Initial Mass Function ever for Cyg OB2, essential to the determination of the total mass of the complex.

The processes leading to the formation of both star clusters and the massive stars within them are currently very poorly understood. Star clusters are

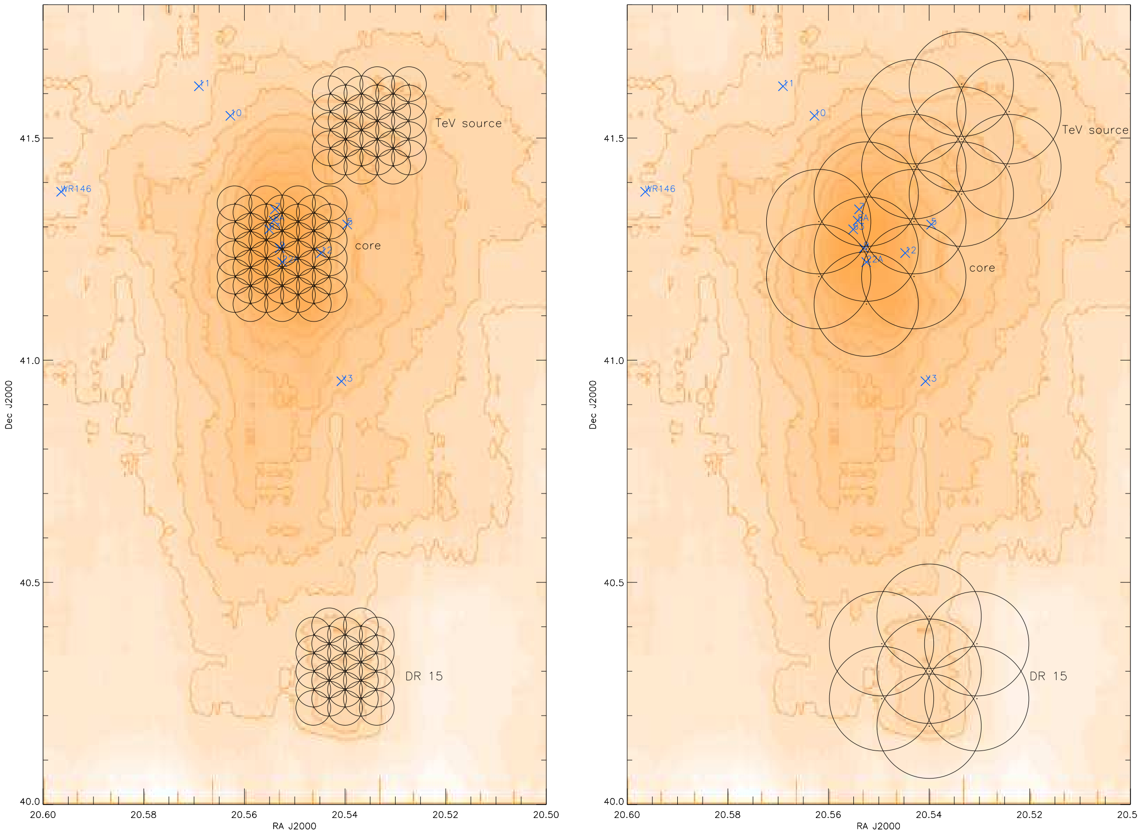

Fig. 2. *Proposed mosaicing of the Cyg OB2 cluster (**left:** C-band, **right:** L-band). The chosen stepsizes of 2.5′ (C-band) and 7.5′ (L-band) provide excellent coverage compatible with the primary beam (including the Lovell telescope for both bands). The background figure is the Knödlseder (2000) outline of the Cyg OB2 association (based on counts from the 2MASS survey). Blue symbols indicate some well-known radio sources (O and WR stars). 97 fields are plotted for C-band, 21 for L-band.*

themselves part of larger star forming complexes containing numerous sub-clusters with a narrow (<10Myr) range of ages. Our proposed multi-epoch observations (Sect. 5) will enable us to dissect the structure of Cyg OB2 in order to verify the physical reality of apparent substructure within Cyg OB2 via the identification of spatially coherent kinematics. In particular, many models of cluster formation predict significant initial substructure that is rapidly erased, the signatures of which should still be present in the kinematics. Detailed three dimensional velocity data is vital for comparison with simulations of different cluster formation scenarios.

Moreover we will be able to utilise these observations to determine the star formation history of Cyg OB2. Current optical observations suggest the presence of at least two epochs of star formation, resulting in Cyg OB2 proper (∼2.4Myr) and a field population of older (4-5Myr) OB supergiants distributed throughout the complex; if such a conclusion is correct we would expect the two populations to be kinematically distinct. Moreover, the IPHAS survey has also revealed the presence of a population of intermediate mass pre-MS Herbig AeBe stars on the periphery of the complex and with an age consistent with formation in the same starburst that yielded Cyg OB2 - are the kinematics of these stars consistent with such an hypothesis?

The expected velocities of stars in Cyg OB2 are uncertain due to the unknown extent of the effect of gas expulsion in this cluster. Assuming a mass of around 5×10^4 $M_\odot$ and a half-mass radius of ∼ 1 pc gives a *virialised* velocity dispersion of ∼ 15 km s^{-1}. However, we do not expect Cyg OB2 to be virialised due to the effects of gas expulsion, rather to be supervirial (e.g. Bastian & Goodwin 2006; Goodwin & Bastian 2006). For an effective SFE (see Goodwin & Bastian 2006) of 1/3rd (which appears quite reasonable from observations of other clusters, see Goodwin & Bastian 2006), the velocity dispersion could be as high as 25 km s^{-1} (possibly even higher if Cyg OB2 was initially in a far denser state than we see today which was probably the case). These estimates are ideally suited to the astrometric precision of e-MERLIN (see Sect. 5).

In addition, recent models of cluster formation suggest that clusters form as clumpy, dynamically cold structures which violently relax. This relaxation induces dynamical mass segregation in a crossing time. This model also predicts that a number of massive stars could be ejected at high velocity from a dense cluster core. This model is in stark contrast to slow, quasi-static models of cluster formation in which the cluster forms in virial equilibrium. Members of the COBRaS team are currently working on detailed dynamical simulations to allow us to distinguish between these models. Consequently, these e-MERLIN observations will provide a critical test of competing models.

A key question regarding regions such as Cyg OB2 is their long term stability against dissolution. Specifically do the stars formed in such complexes disperse into the galactic field population, or can they survive for a Hubble time - in other words are they proto Globular Clusters? Via the determination of the Initial Mass Function and total mass of the complex and the stellar kinematics of the stars we will be able to address this question directly for the first time.

2.3. Binarity and non-thermal radiation

In a binary consisting of two early-type stars (e.g. O+O), the stellar winds collide and electrons are accelerated to relativistic velocities around the shocks in the colliding-wind region. The resulting emission of synchrotron radiation can be detected at radio wavelengths (Dougherty & Williams 2000). The e-MERLIN data from this project will allow us to (i) provide a better determined binary frequency in Cyg OB2, which is an important constraint for evolutionary population synthesis models, and hence having a broad impact on our understanding of galactic chemical evolution; (ii) study statistically the colliding-wind phenomenon and better understand its dependence on stellar and binary parameters; (iii) improve our understanding of the first-order Fermi mechanism responsible for the particle acceleration; and (iv) identify the source of the TeV J2032+4130 γ-rays. These four core areas of binary star science in our project are outlined below.

(i) The presence of non-thermal radiation can be used as a highly efficient way to identify binaries in Cyg OB2, as a single-epoch observation suffices. Fundamentally, where a star in Cyg OB2 is found to have non-thermal emission, a colliding wind and hence a binary companion can be inferred. (Note that cross-checking with existing catalogues, or a single optical or near-IR observation, is still required to make sure that the non-thermal emitter is indeed a massive star and not a PMS object. PMS objects are discussed in Sect. 2.4). Spectroscopic or astrometric determinations of binarity, on the contrary, require multiple observations. Combined with the large extinction in Cyg OB2, this results in much more observing time. A further advantage of the e-MERLIN data is that no confusion by chance alignments on the sky is possible, as these will not generate a colliding-wind region. Finally, the e-MERLIN survey proposed here does not require a pre-selection of targets and is therefore not statistically biased.

The e-MERLIN data will complement existing spectroscopic and astrometric determinations of the binary frequency in Cyg OB2. Classical spectroscopic techniques are better at detecting shorter-period binaries, while astrometric techniques find those with very long periods. The intermediate period range can be well-covered by radio detections of non-thermal emitters: these reveal binaries with periods in the 1-100 yr range. The e-MERLIN observations will therefore find binaries that would otherwise remain undetected.

Knowing the binary frequency over the whole period range is important for evolutionary population synthesis codes. These codes follow a large number of simulated stars taking into account their stellar evolution and their dynamical interactions. Such codes require statistical information about binaries, such as binary fraction, Initial Mass Function, distribution of primary masses and secondary masses, orbital separations and eccentricities (Zinnecker & Yorke 2007, Portegies Zwart et al. 2007, Kiminki et al. 2007, and references therein). Theoretical work on binary statistics specifically for Cyg OB2 is given by Kobulnicky & Fryer (2007). In addition, the binary properties, in particular the mass ratios and separation distributions, are very important to constrain models of star formation. As almost all massive stars appear to form in multiple systems a detailed knowledge of their properties provides a strong constraint on any star formation model (e.g. Goodwin et al. 2007).

Massive binaries are required to explain the observed ratios between numbers of Wolf-Rayet stars, Luminous Blue Variables, Blue and Red Supergiants, compact objects, high and low-mass X-ray binaries and supernovae. Dynamically, they lead to the creation and destruction of binaries, runaway stars, and cooling or heating of the cluster (e.g. Dionne & Robert 2006, Eldridge et al. 2008, Li & Han 2008). In spite of their importance, binary frequencies are quite uncertain: the value for the NGC 6231 cluster was recently revised from 80% down to 63% (Sana et al. 2008) and the IC 1805 value from 80% down to 20% (De Becker et al. 2006). e-MERLIN data will, in combination with existing spectroscopic data, provide a much better determination of the binary frequency for Cyg OB2.

(ii) Only a limited number of non-thermal O+O type colliding-wind binaries are known and have been studied so far (Contreras et al. 1997, Rauw et al. 2002, Blomme 2005, Blomme et al. 2005, 2007, Van Loo et al. 2008). Three of these stars are members of the Cyg OB2 cluster. X-ray data show a considerable number of hard thermal X-ray emitters, which are possibly colliding-wind binaries (Albacete Colombo et al. 2007). We therefore expect that e-MERLIN observations of the dense Cyg OB2 cluster will substantially increase the number of detected O+O colliding-wind binaries. This will allow us to switch from a case-by-case study of these objects to one where a novel, more statistical approach can be taken.

A major point to be addressed by such study is the detectability of radio emission from short-period binaries. Because of the considerable free-free absorption in the stellar winds, the synchrotron emission should not be detectable for a short-period binary (as is confirmed by Wolf-Rayet+OB binaries, Dougherty & Williams 2000). Yet, the 21.9-day period binary Cyg OB2 No. 8A unexpectedly shows orbit-locked radio variations. This indicates either a considerable overestimate of the mass-loss rate, or the presence of a substantial amount of porosity due to clumping (Blomme 2005). To extract this type of information from the proposed e-MERLIN observations we will apply computer codes for stellar atmosphere and wind modelling (CMFGEN, FASTWIND), as well as a simplified version of the Wind3D radiative transfer code (Lobel & Blomme 2008) to make ad hoc models that include clumping and porosity. Conclusions from this part of the proposal are also highly relevant to the exploration of mass-loss mechanisms, discussed in Sect. 2.1.

We expect that the colliding-wind regions will be only marginally resolved by e-MERLIN. In those cases where it is possible, we will use radio-astrometry to follow the movement of the colliding-wind region and thereby determine orbital parameters, such as the period.

(iii) The electrons in the colliding-wind region are accelerated to relativistic velocities by the first-order Fermi mechanism. While the principles of this physical mechanism are quite well understood, a number of problems remain when applying it to real situations. The main issues are explaining the "injection problem" (an energetic seed population is required to start the process), the electron acceleration problem (electrons are more difficult to accelerate than ions because of their smaller gyro-radius), and the feedback of the ion pressure which softens or even destroys the shock (Jones & Ellison 1991, Treumann & Jaroschek 2008).

Colliding-wind binaries provide an excellent laboratory to study the Fermi acceleration mechanism. Modelling has reached a sufficient level of sophistication to allow the detailed interpretation of these data (Pittard & Dougherty 2006) and we intend to apply such models to those binaries where sufficient information is available (such as orbital parameters). Furthermore, the physical conditions in a colliding-wind binary are quite different from those better-known sites of particle acceleration such as interplanetary shocks or supernova remnants. The different range of density, magnetic field and radiation environment in binaries provides substantial new information on the acceleration mechanism.

The models, as constrained by radio data, also provide predictions on the expected gamma-ray flux from these systems. These numbers are important for observations of colliding-wind binaries by current and future high-energy instruments, both ground-based and space-based ones (INTEGRAL, XEUS, HESS, VERITAS). These high-energy observations will then result in further checks on our theoretical understanding of the acceleration mechanism.

(iv) There is currently extensive interest in the identification of likely sources of ultra-high energy emission and cosmic rays. Our mapping of Cyg OB2 is thus designed to also include coverage of the TeV J2032+4130 γ-ray source (see Fig. 2), which has been detected using an imaging atmospheric Cerenkov telescope in the Cyg OB2 region, with a flux of several percent of the Crab Nebula flux (Neshpor et al. 1995, Aharonian et al. 2005). Butt et al. (2006) tried, without success, to find a X-ray counterpart to the TeV source. Radio data have also been used (Paredes et al. 2007, and references therein), and our COBRaS project can contribute significantly to this study. The close spatial association of this TeV source with Cyg OB2 suggests cosmic-ray acceleration by the supersonic stellar winds of many OB stars. Some ideas concerning the origin of the source are given by Torres et al. (2004), Bednarek (2007), and references therein. Finding a counterpart is a crucial step in order to advance the theoretical interpretation of this important source and e-MERLIN observations will be of considerable help here. The γ-rays and the radio synchrotron emission are presumably formed in the same region. The high spatial resolution of e-MERLIN allows the very precise location of the radio emission, and can thereby provide important new constraints on the emission mechanism, and the role of massive OB associations as particle accelerators.

The COBRaS project will provide fresh perspectives on the collective influence (via turbulence, shocks, and high mechanical power density) of 1000's of OB stars in Cyg OB2. Our data will provide an accurate census of OB stars toward the highly extincted region of the TeV source. Deeper radio observations will also be highly valuable to distinguish the non-thermal and thermal components of the emission, and the separation of diffuse and point-like contributions, thus allowing more direct comparisons to multi-wavelength simulations.

2.4. Ongoing and triggered star formation

Until now most pre-main sequence (PMS) T Tauri ($\sim$1 $M_{\odot}$) and their intermediate mass ($\sim$2-10 $M_{\odot}$) Herbig Ae/Be star counterparts have been found in relatively isolated star-forming regions in Gould's belt, but so far we lack the full picture of star formation in more extreme environments such as in and around the large Cyg OB2 association. Recently, Vink et al. (2008) reported the discovery of 50 new PMS candidates towards Cyg OB2 and the H II region DR 15 on its southern periphery. These PMS candidates were found via their strong Hα emission using the INT Photometric Hα Survey of the Northern Galactic Plane (IPHAS). Interestingly, pronounced clustering of T Tauri stars was found roughly a degree south of the centre of Cyg OB2, in an arc close to the HII region DR 15 (see Fig. 2). It is possible that these strong emission-line objects could just be the tip of a much larger population of lower mass pre-main sequence stars that has yet to be uncovered.

T Tauri stars are traditionally divided into Classical T Tauri stars (CTTS) with Hα equivalent widths of 10Å or more, and Weak T Tauri stars (WTTS) with an Hα equivalent width of less than 10Å. This latter population of T Tauri stars presents a major, and possibly even the dominant, component of the PMS population in most star-forming regions, but it is more of a challenge to find the WTTS population with the Hα emission method (of IPHAS) alone.

VLA studies at $\sim$5 GHz have shown that $\sim$10% of WTTS show radio emission at levels of 10^{16}-10^{17} erg s^{-1} Hz^{-1} (e.g. O'Neal et al. 1990) and the majority of WTTS at levels of approximately 10^{15} erg s^{-1} Hz^{-1} (Leous et al. 1991), which is a hundred times more intense than the Sun, indicating that magnetic activity is much stronger during the PMS phase than in later phases of their evolution. Furthermore, for low-mass stars, there is a good correlation between X-ray and radio luminosity (Güdel 2002). We can therefore use known X-ray detections to estimate the radio flux. Figure 3 shows the X-ray luminosity (L_X) vs. mass (M) for the Albacete Colombo et al. (2007) X-ray sources in the core of the Cyg OB2 region (their Fig. 10). We have used the Güdel relation to indicate the 3 sigma detection limit (thick red line; observed flux of 0.010 mJy). The large number of sources that are above the thick line will all be detectable by the proposed e-MERLIN observations. Flaring during the observations will make even more stars detectable. Note also that we plan coverage of Cyg OB2 that is three times larger than that attempted by Albacete Colombo et al. (2007).

The combination of short-term radio variability, particularly compact emission (which is almost never spatially resolved) and the occasional detection of circular polarization provides quite clear evidence that most of the WTTS are non-thermal emitters. The CTTS however show a more resolved structure, and as their spectral indices α are $\leq +0.6$, this suggests the radio emission of most CTTS is thermal in character. The relationship between WTTS and CTTS however is not always clear. It has sometimes been suggested that CTTS evolve rather naturally into WTTS before arriving on the main-sequence, but alternatively it is possible that the environment plays a dominant role by destroying the circumstellar disks.

The radio properties of the Herbig Ae/Be stars appear to be more similar to the CTTS than to the WTTS in that it is predominately thermal in nature and most of it may be the result of a wind, given that the spectral indices for some of these objects are in good agreement with a spectral index of $\alpha = 0.6$, as expected for free-free wind emission, as found in the VLA/ATCA radio study of Skinner et al. (1993). Similarly, radio continuum observations of even younger and sometimes even more massive (with $M > 10M_{\odot}$) young stellar objects (YSOs)

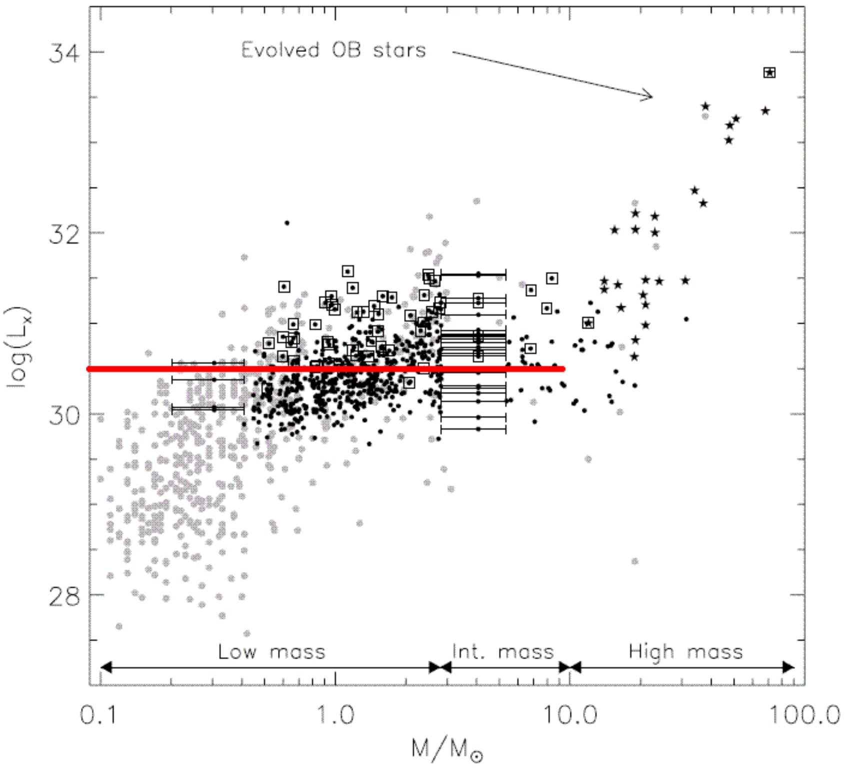

Fig. 3. *The X-ray luminosity (L_X) vs. mass (M) for the Albacete Colombo et al. (2007) X-ray sources in the core of the Cyg OB2 region (their Fig. 10). The 3 sigma e-MERLIN detection limit (red line) is based on the Güdel (2002) relation between quiescent radio and X-ray luminosity. We therefore anticipate the detection of a substantial number of sources.*

yield evidence for ionized mass loss (e.g. Hoare & Garrington 1995).

What is required in order to disentangle the effects of age, stellar mass, and environment are not just large samples, but specifically samples over a range in stellar mass in high-concentration star-forming regions where the potential environmental effect of the OB stars is available. Cyg OB 2 and DR 15 are *ideally suited* for this task. For individual objects, the proposed e-MERLIN survey enables us to compare the radio properties with the Hα emission in relation to the PMS spectral type and rotational velocities, which are believed to play a fundamental role in the production of non-thermal radio emission of WTTS. On the larger scale, the data will allow us to investigate the nature of the ongoing star formation in Cyg OB2 and study the potential scenario in Vink et al. (2008) that the central OB stars triggered star formation in the southern periphery of DR 15.

3. Proposed observations

The proposed deep-field mapping of Cyg OB2 will primarily comprise of ~100 pointings of 6 hours each (i.e. 5 hr effective integration time, and 1 hr overhead for calibration) at 5 GHz, plus an additional 21 (6 hr) maps secured at 1.6 GHz. The mosaicing strategy for the 2 bands is shown in Fig. 2. We of course do not aim to completely cover the very extended association, and have instead selected 3 primary regions to meet the science objectives described in Sect. 2. We plan therefore to target coverage of the 'core' of the cluster, the error box around the TeV source (and neighbouring massive stars) and the DR 15 H II star-forming region. The mapping in Fig. 2 follows the NVSS survey mosaicing strategy of Condon et al. (1998), and adopts a stepsize of $\sim$ beam diameter/$\sqrt{2}$. The circles shown in Fig. 2 have beam diameters of 4.5 arcmin and 16 arcmin for the C and L bands, respectively (i.e. with the Lovell telescope). We plan the inclusion of the Lovell telescope to provide higher sensitivity. Though the inclusion of Lovell decreases the efficiency of mosaicing, its greater sensitivity will be important to our science goals (Sect. 2).

Based on the most recent information[1], a 5 hr effective integration would give 1 sigma *rms* of 2.8-3.6 μJy/beam at 5 GHz and $\sim$ 7.5 μJy/beam at 1.6 GHz. Our total time request for the COBRaS Legacy project therefore amounts to 900 hours, and comprises of 97 × 6hr pointings at 5 GHz (Fig. 2, left), 21 × 6 hr pointings at 1.6 GHz (Fig. 2, right), follow-up (5 GHz) pointings at 2 additional epochs of 10 selected fields (120 hours) over the Legacy period for the astrometric measurements (Sect. 2.2), and a further 72 hours for repeat observations of variable massive stars, binary and YSO sources. A summary of the proposed observation is provided in Table 1. The total time per pointing (on-source) will be around 5 hours. During a single run, we will cycle through a number of fields, in order to obtain the optimum uv-coverage (Sect. 5). The e-MERLIN commissioning time that has been granted to us for a small number of the proposed pointings of Cyg OB2 will greatly assist the determination of the most effective observing technique.

The 5 GHz frequency is the primary band for our purposes: its broad bandwidth allows us to determine not only the flux, but (generally) the spectral index as well. This will allow us to distinguish between thermal and non-thermal radiation. It is also the most sensitive band, allowing the deepest integration. It is intermediate between the two other bands available on e-MERLIN, making it appropriate both for thermal emitters (with a positive spectral index) and non-thermal emitters (with a negative spectral index). The many channels available to cover the bandwidth will also help to recognise maser emission, which we expect for some of our targets. We will nevertheless also observe our target regions of Cyg OB2 at 1.6 GHz (Fig. 2) in order to gain vital additional spectral information, which will be especially important in the most crowded sections of the association.

The very high sensitivity of e-MERLIN will allow us to substantially improve on previous radio work on this cluster. Setia-Gunawan et al. (2003) detected 210 point-like sources at 1400 and/or 350 MHz over the whole Cyg OB2 region. Their 1400 MHz observations had a 1-sigma limit of 400 μJy. By going to 6 cm, we will detect more thermal emitters (since the flux is higher there). The main difference is, however, that we will go considerably deeper. We estimate that at least 10^3 sources will be detected in our survey, which covers only a small area of the Setia-Gunawan et al. survey. Based on the data in Fig. 3 and the census of Knödlseder (2000), we expect that the majority of detections will be PMS objects, For the O stars, based on estimated thermal radio fluxes, all supergiants will be detectable, most giants, but only the brightest main-sequence stars.

4. Synergies with related datasets

The substantial e-MERLIN COBRaS dataset will have direct links to several currently available multi-wavelength datasets involving the team members. These synergies will offer tremendous additional impact for the core science themes outlines in Sect. 2. Examples include the contemperanous Hα and near-IR spectrocopy from the Cygnus Radial Velocity Survey (Kiminki & Kobulnicky), which will be combined witth the 6 cm radio measurements of OB stars to constrain wind clumping properties throughout the entire wind. Reconciling the mass-loss rates from different diagnostics that scan various regions of the outflow will represent a major advance in the field. Furthermore, the unique astrometry of the early type stars that we will obtain with e-MERLIN, will in conjunction with spectroscopic measurements of radial velocities, enable us to produce a very detailed 3-D kinematic map of Cyg OB2.

A 100ks 16' × 16' Chandra survey of the 'core' region of Cyg OB2 has been undertaken (Drake), together with a 50ks Chandra observation of the TeV source region. The stellar mass sensitivity of the 100ks dataset is essentially 'complete' to about 95% for stars down to at least 1 solar mass. These data will not only provide new insights into the ratio of radio to X-ray luminosities of T Tauri stars, but will also uniquely probe the X-ray/radio properties of shocked outflows in OB stars and colliding wind regions.

Optical IPHAS, NIR 2MASS and MIR Spitzer photometry will be used to locate counterparts to e-Merlin sources. The Isaac Newton Telescope Galactic Plane Halpha sur- vey (IPHAS; Drew et al. 2005) has already obtained deep images of Cyg OB2 and its environs in Halpha, r' and i' down to r' = 21. Additional follow-up MMT HectoSpec spectroscopy allows verification of photometrically detected sequences (see Vink et al. 2008 for the DR 15 region), and to examine stellar kinematics in detail. The IPHAS project has already obtained MMT Hectospec spectra of some 4000 objects in the Cygnus X region with 1000 of these in Cyg

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[1] `http://www.merlin.ac.uk/eMERLIN-LegacyProg.pdf`

Table 1. Observations summary

Band	Position of centre			Number of pointings	Polarisation	Total observing time (hours)
	RA	Dec	Region			
C	20 33 10.8	41 13 12	Core	42	RR/LL	252
C	20 32 07.8	41 31 48	TeV Source	30	RR/LL	180
C	20 32 24	40 18 00	DR15	25	RR/LL	150
L	20 32 36.6	41 22 48	Core + TeV Source	14	RR/LL	84
L	20 32 24	40 18 00	DR15	7	RR/LL	42

Repeat observations (astrometry and variability)

Band	Position of centre			Number of pointings	Polarisation	Total observing time (hours)
	RA	Dec	Region			
C	20 33 10.8	41 13 12	All	10	RR/LL	60 × 2 epochs
C	20 33 10.8	41 13 12	All	12	RR/LL	72

OB2 over the last 3 years. The IPHAS/HectoSpec data of the centre of Cyg OB2 and DR 15 show a whole range of PMS characteristics with a wide span in Halpha emission-line strengths. We will correlate the IPHAS Halpha properties with the e-Merlin 6 cm radio properties to identify evolutionary sequences, going beyond simplistic WTTS versus CTTS classification schemes.

The Spitzer IRAC and MIPS data (Hora & Howard) will be used in conjunction with the e-MERLIN survey data to provide a much more complete picture of the regions surrounding locations of current massive star formation. The Spitzer infrared photometry provide a handle on each star's luminosity class and spectral type, information which can then be combined with the radio continuum measurements of associated HII regions or ionized flows. The result will help characterize the effects of the OB associations in their environment, including triggering of new star formation. The Spitzer survey sensitivity enables us to detect a 1 Myr pre-MS star of 0.2 solar masses, sensitive enough to conduct a census of the young stars near the sites of massive star formation. The Spitzer imaging will study the demographics of where the stars form in Cygnus-X (i.e., in isolation, groups, or clusters). We can also map the distribution of stars with disks, to determine the effects of the OB associations on the pre-MS stars, including dispersal of disks due to UV radiation. The relative ages of the stars determined from the Spitzer and near-IR data will allow us to assess models of triggered star formation in the regions surrounding the massive stars. The 8 micron IRAC band is also a tracer of PAH emission, and so can be used to detect PDRs near the UCHII regions and help characterize outflows detected in the e-MERLIN survey, and to determine the large-scale morphologies of the regions.

In regions where outflows exist, IRAC colours can help characterize the extent and nature of the shock in each of the outflows, and together with the radio measurements of the ionized wind (mass-loss rate, for example), the Spitzer and e-MERLIN data can help determine how the outflow drives the shocked material in each object.

5. Technical justification

The proposed observations will therefore require the use of the wide-band, multi-frequency capability of e-MERLIN. Furthermore, in order to perform proper motion measurements using the repeated observations, we seek to fully exploit the facility's astrometric precision.

Sensitivity – The proposed observations require the 2 GHz available bandwidth at C-band (2 polarisations) and the full 0.4 GHz bandwidth at L-band. The expected continuum modes will be required for both frequency observations, with a channel width of 250 kHz and 62.5 kHz for C and L bands respectively, with 512 channels in each sub-band. The sensitivity over a 5 hour observation is $\sim 3\,\mu$Jy/beam and $\sim 7.5\,\mu$Jy/beam at 5 and 1.6 GHz respectively. (This assumes an aperture efficiency of 0.7 and the stated bandwidths). The few OB stars that have already been radio-detected in this Cyg OB2 field have flux densities of the order of a few mJy, hence these should provide signal-to-noise ratios of 1000.

Calibration sources and astrometry – Flux density and point source calibration will be required for which we intend to utilise the established sources used for standard MERLIN observations.

It is an ambition of this proposal to repeat observations of ~ 10 pointings over the course of the possible legacy proposal time. This would preferably include, in addition to the bulk of the observing, two further observing runs of these fields spaced approximately a year apart. This should provide, within the expected accuracy of e-MERLIN at 5 GHz (~0.5-1 mas), the capability of observing changes in position of the order ~1-2 mas/yr for objects within Cyg OB2 (assuming a distance of 1.7 kpc, this corresponds to 8–16 km/s; see Sect. 2.2). This will however, require the use of a good phase calibration source. Whilst it may be possible and in many cases preferable to eventually utilise a strong in-beam phase reference source, initially we intend to use the well established source J2007+4029, the position of which is known to within < 1 mas.

Observing strategy – It has been necessary in consideration of the goals of this proposal to enable coverage of a large area, whilst limiting the total requested observing time to a reasonable amount, hence the expected time-on-source per field is around 5 hours. This will enable the observation of a large portion of Cyg OB2 whilst maintaining good u,v-coverage for the individual pointings and therefore for the required mosaicing. This also results in a realistic Legacy request in total observing time. Figure 4 shows the expected u,v-coverage for a single pointing of the core area. The total 5hr integration is made of four 75 minute integrations covering the total available hour angle range and we expect to adopt a similar strategy to cycle through the required fields during the observing run. This will provide both the best available u,v-coverage per pointing as well as offer natural gaps in which we can include some of the required calibration observations.

To optimise the uniformity and efficiency of these observations, we adopt a mosaic stepsize of ~2.5 and ~7.5 arcmins at C and L bands respectively (see also Fig. 2). These values are well within the $\theta_{pr}/\sqrt{2}$ (where θ_{pr} is the FWHM of the primary beam) constraint which was used for the NRAO VLA Sky Survey (NVSS).

Mosaicing techniques will be required for the full image analysis of these observations. As this is a relatively new technique when using this array, it is expected to become more of a common procedure with e-MERLIN. As such, techniques already developed for producing mosaic images will be utilised, for example the existing tasks within AIPS, MIRIAD (and CASA) software packages, though development of these procedures will be necessary.

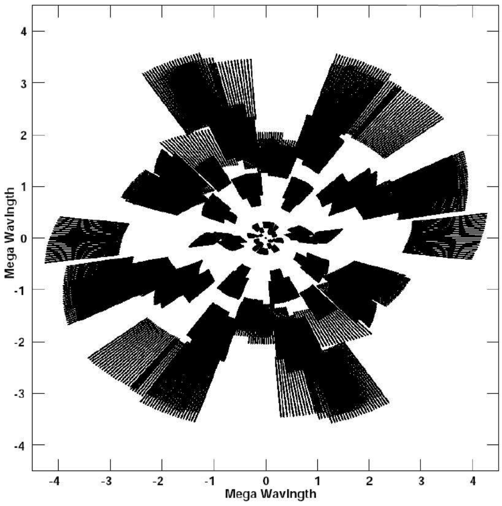

Fig. 4. *Expected u,v-coverage of a C-band single pointing with a total integration time of 5 hrs, from four 75 minute integrations covering the available range in hour-angle.*

6. Data analysis

Data processing – There are two main considerations with regard to the data analysis to achieve the full scientific goals of this proposal. The first will be the development of the data reduction processes which will be a necessary part of the general use of the e-MERLIN array. A Leverhulme-funded RA is already in our COBRaS team (D. Fenech; based at UCL) and currently working with the e-MERLIN team to prepare the required work packages. The second and somewhat more specific consideration is the required processing and outputs for this proposal. We expect to produce four main tiers of data-output: calibrated visibility data, images of individual pointings, full mosaiced images of each of the three regions and scientific analysis outputs such as fluxes and source spectral energy distributions.

Calibration – The calibration of the data is expected to be performed as part of a large pipeline processing of the observations. This will require among other things procedures for phase and amplitude calibration as well as some automated data-editing, as the amount of data produced will be significant and not feasible to edit manually. However, these will be part of the generic procedures used for calibrating data from e-MERLIN and will be implemented for our purposes in a larger pipelined process, which will be developed alongside the generic processes and tailored to the scientific needs where appropriate.

Imaging – The imaging of the individual pointings will necessitate the use of the wide-band algorithms currently under development for e-MERLIN. Use of known practises for wide-field imaging will also be required, such as the removal of confusing sources, using either faceted imaging or the imaging and subtraction of the individual confusing sources. These latter procedures are well practised and can be pipelined in order to image the proposed observations.

The production of the final mosaiced images will be the most technically challenging aspect of this project. Whilst mosaicing is used in radio interferometry, use of an array with differing antennas such as e-MERLIN is rare. As such, there will be developments required in order to achieve the full scientific return from these data. However, again it should be noted that this is likely to become more of a common practise and hence developments of this nature will be necessary for the standard use of the array.

It is expected that initially, existing tasks within current software such as AIPS, MIRIAD and CASA (e.g. LTESS) can be used to produce mosaics from images of the individual pointings, and that mosaicing directly from the visibility data should be possible at a later stage.

In addition to this proposal, we have been granted time for preliminary observations during the e-MERLIN commissioning phase, which will be of significant benefit in the success of the proposed observations. This will enable the optimisation of (and the correction of any unforeseen issues with) the planned observing procedure. It will also provide a test-base to develop the required processing techniques for the full legacy proposal.

Analysis – Initially, the data will be processed and used to locate sources within the images. This will require a pipeline to locate and extract position and flux density information for these sources at both L and C bands. This process will also include the production of spectral energy distributions from flux density information extracted at regular intervals within the observed bands. This will begin the identification process of the observed sources and distinguish between thermal emitters (individual massive stars) and non-thermal ones (colliding-wind binaries or PMS). Cross-correlations with existing catalogues will then distinguish between PMS and massive stars.

Data archiving – Both the scientific images produced to address the questions of this proposal and the resulting table of sources containing extracted information (such as flux density values) will require archiving. These will be made available to the community within the existing VO framework. This will include where necessary the addition of metadata (for example information required for proper interpretation of the FITS images). The extracted source information will be made available for use with TOPCAT in an appropriate format. It is also the intention to make available to the community the calibrated data for use to address future scientific archival research that is not necessarily part of this proposal. Given that the likely format of these data will be either an AIPS UVFITS file or a CASA measurement set, it may not be suitable for direct access via the available VO software. In such a case, steps will be taken to provide information about, and links to the data through the VO framework.

It is not expected that longer than the 12 month proprietary period will be required for these observations and, where feasible, all pipelines will be written using the python/parseltongue languages.

7. Management and resources

We have assembled a highly experienced, international team to ensure timely progress and maximum exploitation during all phases of the COBRaS Legacy project. Dedicated ‘engineering’ and technical support will be provided by Danielle Fenech, who is a UCL-based Leverhulme-funded RA (PI - Raman Prinja), already engaged in preparing work packages associated with outstanding wideband calibration and fore-ground subtraction problems with e-MERLIN data reduction. The individual responsibilities are listed in Table 2, though we also anticipate significant overlapping effort during the data analysis and interpretation stages. Preliminary pairs of subject leads in each core science area are identified in Table 2 (in bold face); we plan to hold a kick-off workshop at UCL immediately after the outcome of the Legacy proposal is known, where the subject leads, funding options, strategy and publications will be confirmed.

Table 2. Team member roles (preliminary subject leads in **bold face**).

Coordination
Raman Prinja (UCL, UK)
Data reduction and pipelines
Danielle Fenech (Dedicated e-MERLIN RA)
Jeremy Yates (e-MERLIN data reduction)
Joan Vandekerckhove (Data reduction specialist)
Ronny Blomme (Data reduction expertise)
Anita Richards (e-MERLIN team; VO)
Dugan Witherick (VO; web site management)
Stewart Eyres (MERLIN expert/source detection)
Massive stars: Mass loss, clumping and evolution
Raman Prinja (stellar winds; mass-loss)
Ronny Blomme (Radio mass-loss studies)
Mike Barlow (Radio mass-loss studies; Herschel)
Ian Howarth (Mass loss; evolution)
Allan Willis (WR stars; LBVs)
Phil Diamond (Evolved stars; mass loss)
Jorick Vink (Mass loss; theory)
Salvo Scuderi (Radio mass-loss studies)
Paul Crowther (Evolution; CMFGEN)
Derck Massa (Winds; clumping; UV spectra)
Cluster dynamics and astrometry
Simon Clark (Kinematics; census studies)
Simon Goodwin (Astrometry; dynamics)
Janet Drew (Cluster formation; dynamics)
Dan Kiminki (Kinematics)
Chip Kobulnicky (Kinematics)
Jacco van Loon (Cluster dynamics)
Danielle Fenech (Cluster dynamics)
Martin Ward (Cluster formation)
Binarity and non-thermal emission
Ian Stevens (Colliding winds)
Jeremy Drake (Chandra Legacy)
Felix Aharonian (TeV source)
Ronny Blomme (Non-thermal radiation)
Julian Pittard (Colliding winds; theory)
Sean Dougherty (WR+O binaries)
Raman Prinja (Wind clumping)
Ian Howarth (High-mass binaries; rotation)
Nick Wright (Chandra Legacy)
Dan Kiminki (Kinematics; RV survey)
Chip Kobulnicky (Kinematics; spectroscopy)
Stewart Eyres (Evolved stars)
Ishwara Chandra (Non-thermal emission; GMRT)
Ongoing and triggered star formation
Jorick Vink (IPHAS; T Tauri)
Joseph Hora (Spitzer Cygnus X Legacy)
Janet Drew (IPHAS; T Tauri)
Simon Clark (Triggered star formation)
Mike Barlow (Triggered star formation)
Jeremy Yates (Triggered star formation)
Howard Smith (Spitzer Cygnus X Legacy)

8. Legacy status

The Cyg OB2 radio survey we propose is a coherent programme designed to conduct substantial deep-field mapping of one of the most massive OB associations in our Galaxy, and which hosts a tremendously diverse stellar population. The Legacy status is essential to permit us to assemble the requisite substantial datasets, which are homogeneous in sensitivity limits, uniform and based on systematic mosaics. We aim to establish an unbiased physically based dataset of Cyg OB2 of vast diagnostic potential, that simply cannot be achieved via conventional PATT proposals.

The core science themes discussed in this proposal will draw the immediate attention of the assembled COBRaS team and will undoubtedly spawn related follow-up observations. We anticipate follow-on studies that exploit multi-wavelength datasets, including specifically the combination with already established Cygnus X Legacy surveys of Spitzer and IPHAS, plus available and planned Chandra Legacy data (see Sect. 4 and Table 2). Additional multi-waveband studies of Cyg OB2 are expected to combine e-MERLIN data with the GMRT (e.g. 610 MHz), JCMT (SCUBA-2), Herschel and JWST facilities.

The COBRaS project will also provide an excellent platform for archival research. The dataset will permit research to be carried out in numerous science areas that extend beyond our core interests (Sect. 2). We anticipate, for example, substantial follow-on science returns relating to the detection of a large and diverse range of foreground objects (incl. F, K and M-type stars) and possibly embedded SNRs. The potential for archival science represents a clear Legacy core of the COBRaS project. Furthermore, the value added products from our project will extend over a valuable range that includes databases, catalogues, and atlases, all of which will be distributed to the community. We also plan engaging public Outreach exercises, based on striking e-MERLIN radio maps of the cluster, and additional images that combine with other telescopes to reveal large-scale (dust and gas) structure.

The overall COBRaS delivery of large coherent datasets, substantial follow-on and archival science opportunity, and extensive data products, makes this an e-MERLIN project of genuine lasting value to the broad astronomical community.

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