# A single fast radio burst localized to a massive galaxy at cosmological distance

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Fast radio bursts (FRBs) are brief radio emissions from distant astronomical sources. Some are known to repeat, but most are single bursts. Nonrepeating FRB observations have had insufficient positional accuracy to localize them to an individual host galaxy. We report the interferometric localization of the single-pulse FRB 180924 to a position 4 kiloparsecs from the center of a luminous galaxy at redshift 0.3214. The burst has not been observed to repeat. The properties of the burst and its host are markedly different from those of the only other accurately localized FRB source. The integrated electron column density along the line of sight closely matches models of the intergalactic medium, indicating that some FRBs are clean probes of the baryonic component of the cosmic web.

osmological observations have shown that baryons constitute 4% of the energy density of the Universe, of which only about 10% is in cold gas and stars (*I*), with the remainder residing in a diffuse plasma surrounding and in between galaxies and galaxy clusters. The location and density of this material have been challenging to characterize, and up to 50% of it remains unaccounted (*2*).

Fast radio bursts [FRBs (*3*)] are bright bursts of radio waves with millisecond duration. They can potentially be used to detect, study, and map this medium, as bursts of emission are dispersed and scattered by their passage through any ionized material, including the intergalactic medium (IGM). If the emission is linearly polarized and any of the media are magnetized, the burst is also subject to Faraday rotation (i.e., the frequency-dependent rotation of the plane of linear polarization due to its passage through a magnetized plasma) (*4*).

Detailed studies of the medium, and the bursts themselves, require localization of bursts to host galaxies, so that burst redshifts and their propagation distances can be determined. To date, only one source (FRB 121102) has been localized (5) with sufficient accuracy to identify a host. It is also one of only two FRBs known to repeat (6). The burst localization was made through radiointerferometric detections of repeated bursts. The burst source lies in a luminous radio nebula (5) within a dwarf galaxy with high star formation rate per unit stellar mass, at redshift z = 0.19 (7). This has led to the hypothesis that bursts are produced by young magnetars embedded in pulsar wind nebulae (8), with the host galaxy properties suggesting an indirect connection between FRBs and other transient events that are common in this type of galaxy, such as superluminous supernovae and long-duration gamma-ray bursts.

The relationship between the source of FRB 121102 and the larger FRB population is unclear (9-11). Many sources have not been observed to repeat despite extensive campaigns spanning hundreds to thousands of hours (10, 12). The progenitors and mechanism by which burst emission is generated remain uncertain. Localizing examples of further bursts, including those from a population that have not repeated, is re-

quired to determine their nature and establish whether they can be used as cosmological probes.

### Localizing fast radio bursts with ASKAP

The Australian Square Kilometre Array Pathfinder [ASKAP (13)], a 36-antenna radio interferometer, has a specially designed mode capable of directly localizing dispersed pulses, such as FRBs (14). Each of the 12-m antennas has been placed in a quasi-random configuration with baselines extending to 6-km lengths, resulting in a maximum angular resolution of 10 arcsec at a frequency of 1320 MHz, enabling positions to be measured to a statistical precision of ~10 arcsec/(2 × S/N), where S/N is the source signal-to-noise ratio.

The antennas are equipped with phased-array feed receivers (15), each of which can form 36 simultaneous dual-polarization beams on the sky using digital beamforming, producing a total ~30 deg<sup>2</sup> field of view. For burst detection, the beamformers produce channelized autocorrelation spectra for both linear polarizations of all beams, with an integration time of 864  $\mu$ s and channel bandwidth of 1 MHz in these observations. We used 336 channels centered at 1320 MHz. A real-time detection pipeline incoherently adds the spectra from all available antennas (24 antennas in these observations) and polarization channels, then searches (16) the result for dispersed pulses (17).

Burst localization is completed with a second data product that uses both the amplitude and phase information of the burst radiation. The beamformers store samples of the complex electric field for all beams and both polarizations in a ring buffer of 3.1 s duration, with the oldest data being continuously overwritten by new data. The data are saved for offline interferometric analysis only when the pipeline identifies a candidate. For the searches reported here, the triggering required pulses with widths less than 9 ms and S/N > 10.

Previous searches with ASKAP used antennas pointed in different directions to maximize sky coverage (10, 16). In contrast, our observations used antennas all pointed in the same direction. enabling the array to act as an interferometer capable of sub-arcsecond localization with a 30 deg<sup>2</sup> field of view. We targeted high-galactic latitude fields (galactic latitude  $|b| \sim 50^{\circ}$ ), which had been observed previously (10, 16), and Southern circumpolar fields. The high-latitude fields were observed regularly through 2017 and early 2018 for a total duration of >12,000 hours (10), enabling us to put constraints on burst repetition. For daytime observations, circumpolar fields were observed to enable prompt follow-up from Southern Hemisphere optical telescopes.

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# The detection of FRB 180924

We detected a burst (FRB 180924; Fig. 1) with S/N of 21 in one of the high–Galactic latitude fields. The search pipeline identified the burst 281 ms after the dispersed pulse swept across the lowest-frequency channel and triggered the download of the buffer containing the burst.

The properties of the burst, listed in Table 1, and the strong spectral modulation (see Fig. 1B) are similar to the previous examples detected with ASKAP in lower-sensitivity searches (10, 18), which suggests that they belong to the same population. The dispersion measure (DM) of the burst, which is the integrated free electron content along the line of sight weighted by the rest frame frequency while passing through the dispersing medium, is  $361.42 \pm 0.06$  pc cm<sup>-3</sup> and the burst fluence is  $16 \pm 1$  Jy·ms (1 Jy =  $10^{-26}$  W Hz<sup>-1</sup> m<sup>-2</sup>). The burst is 80% linearly polarized and shows evidence for only modest Faraday rotation. The measured strength of the Faraday rotation (i.e., the rotation measure) is  $14 \pm 1$  rad m<sup>-2</sup> (17). The galactic foreground contribution to the Faraday rotation along high-latitude lines of sight is low; the Milky Way Faraday rotation along this line of sight is predicted (19) to be 7.5 rad  $m^{-2}$ . The pulse shows evidence for scatter broadening with a scattering time scale  $\tau_s = 580 \pm 20 \ \mu s$  at a frequency of 1.2 GHz (17).

### A sub-arcsecond localization

We localized the burst using an image made from the 3.1 s of voltage data, produced with techniques developed for long-baseline radio interferometry. Two teams blindly analyzed the data, using different pipelines and codes, and derived the same initial source positions (*17*). In a refined, coherently formed, optimally weighted image, the burst was detected with S/N of 194, from which the position was measured with a statistical uncertainty (from thermal noise alone) of 0.04 arcsec.

To identify a host galaxy, it is necessary to tie the radio image to an optical reference frame. We registered the position of the burst on a deep Dark Energy Survey [DES (20)] optical image of the region by bootstrapping the radiointerferometric image of the burst to a deeper radio observation of the field that can subsequently be referenced to a standard sky coordinate system (17). In addition to the burst, three constant (nontransient) radio sources were also detected in our 3.1-s ASKAP image. We compared their measured positions with those obtained from phase-referenced observations with the Australia Telescope Compact Array (ATCA), observing in the same frequency band as ASKAP. One source has both a precise radio position (uncertainty 0.004 arcsec) measured with very long baseline interferometry and an optical position from DES. We corrected a small residual offset in the DES image relative to the optical reference frame by cross-matching stars in the DES images that had been cataloged by the Gaia mission (17, 21). The positions agree with each other within their uncertainties, thus confirming that the radio and optical frames are well aligned. We estimate the combination of statistical and systematic uncertainty in the burst's position to be 0.12 arcsec in both right ascension and dec-





lination (17). The position of the burst is right ascension  $21^{h}44^{m}25.255^{s} \pm 0.008^{s}$ , declination –  $40^{\circ}54'00.1'' \pm 0.1''$  (equinox J2000).

#### The burst host galaxy

The sub-arcsecond localization for FRB 180924 allows us to uniquely identify the host by combining public observations from the Dark Energy Survey (20) with deeper images of the field we obtained with the Very Large Telescope (VLT), long-slit spectra with the Gemini-South telescope, and integral-field spectra with the Keck II telescope and the VLT [see (17) for details of instrumental setups].

Figure 2 shows a deep VLT image of the field around the burst position. The burst source is located  $0.8 \pm 0.1$  arcsec from the center of galaxy DES J214425.25-405400.81 (galaxy A in Fig. 2A) cataloged by the DES (20). Keck observations establish the spectroscopic redshift of this galaxy to be z = 0.3214, based on the ionized oxygen emission from diffuse gas in the galaxy and calcium absorption lines from its stellar component (Fig. 2B). The redshift was confirmed with spectroscopic observations of the galaxy with Gemini-South (Fig. 2, C and D), which showed line emission from additional species at the same redshift, including the first two (hydrogen) Balmer transitions (H $\alpha$  and H $\beta$ ) and ionized nitrogen (17). The deeper images obtained with the VLT show two other nearby objects that were also both detected in the integral-field spectra. There is faint ionized oxygen emission from a dwarf galaxy, labeled galaxy B in Fig. 2, at z = 0.384approximately 3 arcsec to the north west of the host and ~3.6 arcsec from the position of FRB 180924. This corresponds to a projected distance of 19 kpc at the redshift of this galaxy. A third galaxy with a redshift z = 0.50055 (galaxy C in Fig. 2) is located 3.5 arcsec northeast of the FRB position, at a projected distance of 21 kpc. We rule out association of the burst with these galaxies with high confidence (17).

We derive the properties of the host galaxy A by combining photometry from public surveys in optical (20) and near-infrared wavelengths [from Wide-field Infrared Survey Explorer (WISE) 3.6- and 4.5-µm images] (22) with our optical imaging and spectroscopy (Figs. 2 and 3), using standard techniques (17). The host properties are consistent with a massive lenticular or earlytype spiral galaxy. The stellar population has a total mass of 2.2  $\times$  10<sup>10</sup>  $M_{\odot}$  (where  $M_{\odot}$  is the solar mass) and is dominated by an old stellar population with an age  $t_{age} > 4$  billion years. The galaxy shows nebular emission lines with ratios consistent with gas excited by a harder spectrum than the ionizing flux of a star-forming population, characteristic of low-ionization narrowemission line region (LINER) galaxies (23). We demonstrate this by measuring the strength of forbidden transitions of singly ionized nitrogen ([N II]) and doubly ionized oxygen ([O III]), relative to, respectively,  $H\alpha$  and  $H\beta$ , and comparing to a well-studied sample of galaxies (24) (Fig. 4). The host galaxy resides in the region of phase space occupied by LINER galaxies (25).

The galaxy also shows the presence of interstellar dust, which is attenuating the opticalwavelength emission. The ratio of strength of  $H\alpha$ to  $H\beta$ , combined with multiband photometry, suggests that there is internal extinction by dust within the galaxy (extinction  $A_V \approx 1$  magnitude, i.e., the optical V band is attenuated by a factor of ~2.5). In principle, the measured hydrogen emission lines can be used to constrain star formation in the galaxy. Although the data allow for a nonzero star formation rate, we report an upper limit of <2.0  $M_{\odot}$  per year, because we attribute a large fraction of the dust-corrected  $H\alpha$ luminosity (26) to the LINER component. The galaxy has a compact morphology described by a Sérsic profile (27) with index  $n = 2.0 \pm 0.2$  and an effective radius of  $2.79 \pm 0.01$  kpc. The burst is located exterior to ~90% of the galaxy's stellar light (17).

We detect no radio-continuum emission from the burst location or anywhere within its host. We searched the host galaxy for radio emission with ATCA in a continuous band from 4.5 to 8.5 GHz, at 1 and 10 days post-burst, and with ASKAP in a band from 1.1 to 1.3 GHz 2 days post-burst. We set  $3\sigma$  flux-density limits on the emission of 20 µJy at a central frequency of 6.5 GHz and 450 µJy at 1.3 GHz (*17*).

No repeated bursts were observed from this direction, either before or after the burst was detected. We conducted sensitive searches with the Parkes radio telescope for a duration of 9 hours starting 8 days post-burst and a further 2 hours, 23 days post-burst (17). No pulses were found above a  $10\sigma$  limit of  $0.5{w_{ms}}^{1/2}$  Jy·ms for widths of  $w_{\rm ms}$  ms. Likewise, no pulses were found in 720 hours of observations of the field as part of previous, less sensitive, single-antenna observations with ASKAP (10) conducted between March 2017 and February 2018. These searches place  $10\sigma$  limits on fluence of  $25w_{ms}^{1/2}$  Jy·ms, for pulses of width  $w_{\rm ms}$  ms (17). The burst was detected in a campaign in which the field was observed with a  $10\sigma$  fluence limit of  $5{w_{\rm ms}}^{1/2}$ Jy·ms in a total observing time of 8.5 hours.

### Comparison to FRB 121102 and its host

The properties of the burst and its host differ markedly from those of the repeating burst source FRB 121102 and its host galaxy. The host galaxy of FRB 180924 is a lenticular or early-type spiral with negligible or low rates of star formation. In contrast, the host of the FRB 121102 is a factor of 30 less luminous, and is a low-mass, lowmetallicity (low abundance of heavy elements), dwarf galaxy with a high star formation rate (28). Such dwarf galaxies are sites of high-mass star formation and are frequent hosts of superluminous supernova and gamma-ray bursts (29). The two galaxies reside in completely different regions of the galaxy-type phase space defined by their emission lines (Fig. 4).

The burst source environments are also very different. FRB 121102 resides in a radio nebula containing highly magnetized plasma; its bursts have high rotation measures [RM ~  $10^5$  rad m<sup>-2</sup> (*30*)], with the bursts showing a 10% decrease

over about a year (30). A large dispersion measure contribution is inferred from FRB 121102's host and local environment [55 to 225 pc cm<sup>-3</sup> (7, 28)], indicating that it propagates through (and is likely embedded in) a dense, highly magnetized and dynamic plasma. The source of the repeating FRB 121102 is also colocated with a compact radio source with luminosity 1.8  $\times$  10<sup>22</sup> W Hz<sup>-1</sup> (5) at 6 GHz, whereas FRB 180924 shows no evidence for persistent associated radio emission at a limit about one-third as luminous as the luminosity of the FRB 121102 compact source.

FRB 180924 has not been observed to repeat, despite extensive observations at low sensitivity with ASKAP and sensitive contemporaneous observations with the Parkes radio telescope. It is difficult to assess the statistical significance of the nonrepetitions from a single burst source. Although the repetition rate of FRB 121102 is poorly characterized, the activity appears to be clustered into time scales of weeks to months (31, 32) followed by long periods of inactivity. Sensitive searches with the Parkes radio telescope shortly after FRB 180924 was discovered did not detect any further bursts on time scales of weeks to months.

The differences between FRB 180924 and FRB 121102 (the only other well-localized burst source) suggest either that there could be two different populations of burst progenitors, or that progenitors occur in diverse environments. Models assuming a single progenitor class for bursts must reproduce the diversity in phenomenology and environments observed for burst sources.

**Table 1. Properties of FRB 180924 and its host.** The fluence is derived from incoherent sum data. The implied isotropic energy density has been corrected to emission rest frame using a spectral index of –1.6 (*18*). The redshift inferred from the DM has large scatter about the mean trend (*35*), as discussed in the main text and the supplementary materials. The Milky Way DM component was estimated from the NE2001 model (*33*).

#### **FRB** properties

Dispersion measure (DM)	361.42 ± 0.06 pc cm <sup>-3</sup>
Arrival time at 1152 MHz	24 September 2018, 16:23:12.6265 UT
Fluence	16 ± 1 Jy∙ms
Pulse width	1.30 ± 0.09 ms
Right ascension (J2000)	21h44 <sup>m</sup> 25.255 <sup>s</sup> ± 0.008 <sup>s</sup>
Declination (J2000)	-40°54′00.1″ ± 0.1″
Galactic longitude	0.742467 deg
Galactic latitude	–49.414787 deg
Incoherent detection S/N	21
Image frequency-weighted S/N	194
Fractional linear polarization	80 ± 10%
Spectral modulation index	0.80
Decorrelation bandwidth	8.5 MHz
Rotation measure	14 ± 1 rad m <sup>-2</sup>

Host galaxy properties	
0.3214 ± 0.0002	
21 <sup>h</sup> 44 <sup>m</sup> 25.25 <sup>s</sup>	
-40°54′00.81″	
20.54 ± 0.02	
21.62 ± 0.03	
21.14 ± 0.02	
1.08 ± 0.04	
0.41 ± 0.03	
16.9 ± 0.1	
16.1 ± 0.2	
<450 μJy	
<20 µЈу	
	properties $0.3214 \pm 0.0002$ $21^{h}44^{m}25.25^{s}$ $-40^{\circ}54'00.81''$ $20.54 \pm 0.02$ $21.62 \pm 0.03$ $21.14 \pm 0.02$ $1.08 \pm 0.04$ $0.41 \pm 0.03$ $16.9 \pm 0.1$ $16.1 \pm 0.2$ $<450 \mu Jy$

## Inferred properties

Implied FRB isotropic energy density	$6 \times 10^{31}  \text{erg Hz}^{-1}$
Redshift inferred from DM (41)	0.34
DM Milky Way disk	40 pc cm <sup>-3</sup>
DM Milky Way halo	60 pc cm <sup>-3</sup>



Fig. 2. Host galaxy of FRB 180924. (A) VLT/FORS2 g'-band image showing the host galaxy of FRB 180924, labeled A. The burst location uncertainty is shown by the black circle. Two faint background galaxies, labeled B and C, are also visible at the right and upper left (see supplementary text). (B) Keck Cosmic Web Imager (KCWI) spectrum (17) of the FRB 180924 host, showing the detection of forbidden-line ionized oxygen emission [O II] and calcium absorption, which set the FRB redshift z = 0.3214. The oxygen emission is attributed to gas ionized by a hard ionizing spectrum. The absorption lines are stellar. (C) Section of Gemini Multi Object Spectrograph (GMOS) spectrum. The spectrum shows (hydrogen) Balmer line  $H\alpha$ , nitrogen, and sulfur emission at a redshift consistent with the lines detected in the Keck spectrum. (D) Section of GMOS spectrum showing detections of the Balmer line  $\ensuremath{\mathsf{H}\beta}$  and forbidden line emission from doubly ionized oxygen ([0 III]).



# Using the burst as an intergalactic and cosmological probe

The dispersion and redshift of FRB 180924 can be used to test models of the free electron column density of the IGM. We modeled the dispersion to be the sum of components from the Milky Way's disk and halo, the IGM, and the burst's host galaxy. Using models of the Milky Way, we infer a dispersion contribution from the disk (33) to be 40 pc cm<sup>-3</sup> and the halo (34) to be 60 pc cm<sup>-3</sup>. A simple model of the IGM based on the average baryon density and ionization fraction of the Universe (34) predicts the intergalactic component of the dispersion to be  $307 \text{ pc cm}^{-3}$  out to the redshift of the host. The sum of these components exceeds the dispersion of FRB 180924 by 46 pc cm<sup>-3</sup> without including any contribution from the host galaxy interstellar medium (ISM) and its halo. The errors in the Milky Way and halo components are expected to be small ( $\sim 30 \text{ pc cm}^{-3}$ ) relative to the total dispersion budget (34), so the main source of uncertainties in estimating the host dispersion contribution is the IGM component. The latter depends on the distribution of foreground circumgalactic gas with respect to the associated dark matter halos (a process strongly influenced by galactic feedback) and sample variance along a given sight line.

We used an IGM model that takes these uncertainties into account (*35*) to derive posterior probability distributions on the host electron densities under a range of assumed halo shapes (*17*). The mean host contribution to the dispersion inferred from these models, corrected for host redshift, is in the range 30 to 81 pc cm<sup>-3</sup>, with 95% upper limits ranging from 77 to 133 pc cm<sup>-3</sup>. This indicates that the dispersion of FRB 180924 is consistent with models of the IGM, provided that the host contribution is much smaller than that found for FRB 121102.

There are two plausible locations for the burst temporal broadening: in the host galaxy or in an intervening galaxy halo. It is unlikely that the burst is scattered by the diffuse extragalactic medium (*36*). Similarly, the temporal broadening in the Milky Way at high latitudes is predicted to be small at these frequencies [<1  $\mu$ s (*33*)]. If the burst is scattered by the host galaxy, the medium has

increased turbulence relative to the Milky Way (*17*). Substantially lower levels of turbulence would be required in an intervening galaxy halo to produce the measured scatter broadening, because turbulence near the midpoint between the source and observer produces relatively more broadening than if the same level of turbulence were at either end. For a fixed turbulence strength, relative to an ISM line of sight (assuming a distance  $D_{\rm ISM} = 10$  kpc in the host galaxy's ISM), the extragalactic line of sight has an enhancement in temporal broadening by a factor  $D_{\rm IGM}/D_{\rm ISM} \sim 10^5$ , for lines of sight of at a distance  $D_{\rm IGM} = 10^6$  kpc in the IGM (*36*).

The burst can be used to quantify the mean magnetization of the dispersing plasma along the line of sight. Assuming both a uniform magnetic field and electron densities along the line of sight, and using the excess Faraday rotation and dispersion of this burst, we set an upper limit on the magnetic field strength in the IGM parallel to the line of sight of  $\leq 30(1 + z_{EG})$  nG, where  $z_{EG}$  is the mean redshift of the magnetized plasma. These constraints are similar to those found for previous bright bursts (*12*) and

are consistent with models of magnetization in extragalactic plasma (*37*).

On the basis of our sub-arcsecond localization of FRB 180924 to a galaxy at z = 0.3214, we expect single-pulse FRBs to be potential probes of the IGM at cosmological distances. First, the rate of detection of single-event bursts is a factor of >30 greater than those that have been found to repeat, so we expect them to provide a larger statistical sample. Second, if the environment of



**Fig. 3. Spectrophotometric properties of FRB 180924's host galaxy.** (**A**) Photometric measurements of the host galaxy from the Dark Energy Survey first Data Release (DES-DR1) and the WISE near-infrared observations. Spectral energy distribution modeling yields an estimated stellar mass of  $M_* = 2.2 \times 10^{10} M_{\odot}$  dominated by a modestly reddened, old stellar population ( $t_{age} > 4$  billion years). (**B** to **D**) Nebular line emission of the FRB 180924 host from the VLT/MUSE data cube. Penalized pixel fitting (pPXF) models fitted to these data (green lines) yield [O III]/H $\beta$  and [N II]/H $\alpha$  line ratios characteristic of early-type LINER galaxies. (B) Spectrum includes hydrogen Balmer line (H $\alpha$ ) and forbidden nitrogen ([N II]). (C) Spectrum includes forbidden oxygen ([O III]) transitions.

#### Fig. 4. Diagnostic plot for characterizing emission line galaxies. The green points

show the distribution of ~75,000 nearby (0.02 < z < 0.4) emission-line galaxies from the Sloan Digital Sky Survey, restricted to have S/N > 5. The intensity scaling is logarithmic to accentuate regions away from the dominant, star-forming locus. Black lines separate the star-forming galaxies [solid (25)] from sources dominated by hard spectra [dashed (39)]; the dotted line separates sources designated as active galactic nuclei into either Seyfert or LINER galaxies (40). The host



galaxy of FRB 180924 (red circle) is well offset from the star formation locus and is most consistent with LINER emission. In contrast, the host galaxy of the repeating FRB 121102 falls firmly in the star-forming sequence (blue star). Its  $[N \parallel]/H\alpha$  ratio is formally an upper limit.

FRB 180924 is representative, this population of bursts have low host contributions to burst dispersion and rotation measure, so there will be relatively small uncertainties in the measurements of the density and magnetization of the IGM out to large distances. Finally, if the hosts of other bursts are similarly luminous as the host of FRB 180924, identifying hosts at high redshift will be easier than if bursts are exclusively hosted in dwarf galaxies (*38*), like the host galaxy of FRB 121102.

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authors declare no competing interests. Data and materials availability: Data from observations collected at the European Southern Observatory under ESO programs 0102.A-0450(A) and 2102.A-5005(A) are available from http://archive.eso.org/. Observations obtained at Gemini Observatory under program GS-2018B-Q-133 can be retrieved from https://archive.gemini. edu/. Observations from the Australia Telescope Compact Array under program C3211, and the Parkes radio telescope under program P958, can be retrieved from https://atoa.atnf.csiro. au/. Keck observations were obtained under project ID U012 2018B and can be retrieved from www2.keck.hawaii.edu/koa/. Further datasets used in this paper are available from the CSIRO Data Access Portal at https://doi.org/10.25919/ 5d09d22f2c004: seven visibility data sets used to calibrate and determine the localization of FRB 180924, the ATCA image used for astrometry, calibrated optical images and spectra, and radio images. Data reduction scripts

and code written by the co-authors for this project are available from the craft git repository, https://bitbucket.csiro. au/scm/craft.git, and the psrvlbireduce repository, https://github.com/dingswin/psrvlbireduce.

#### SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/365/6453/565/suppl/DC1 Materials and Methods Supplementary Text Figs. S1 to S7 Tables S1 to S9 References (42–97)