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Unexpected Circular Radio Objects at High Galactic Latitude

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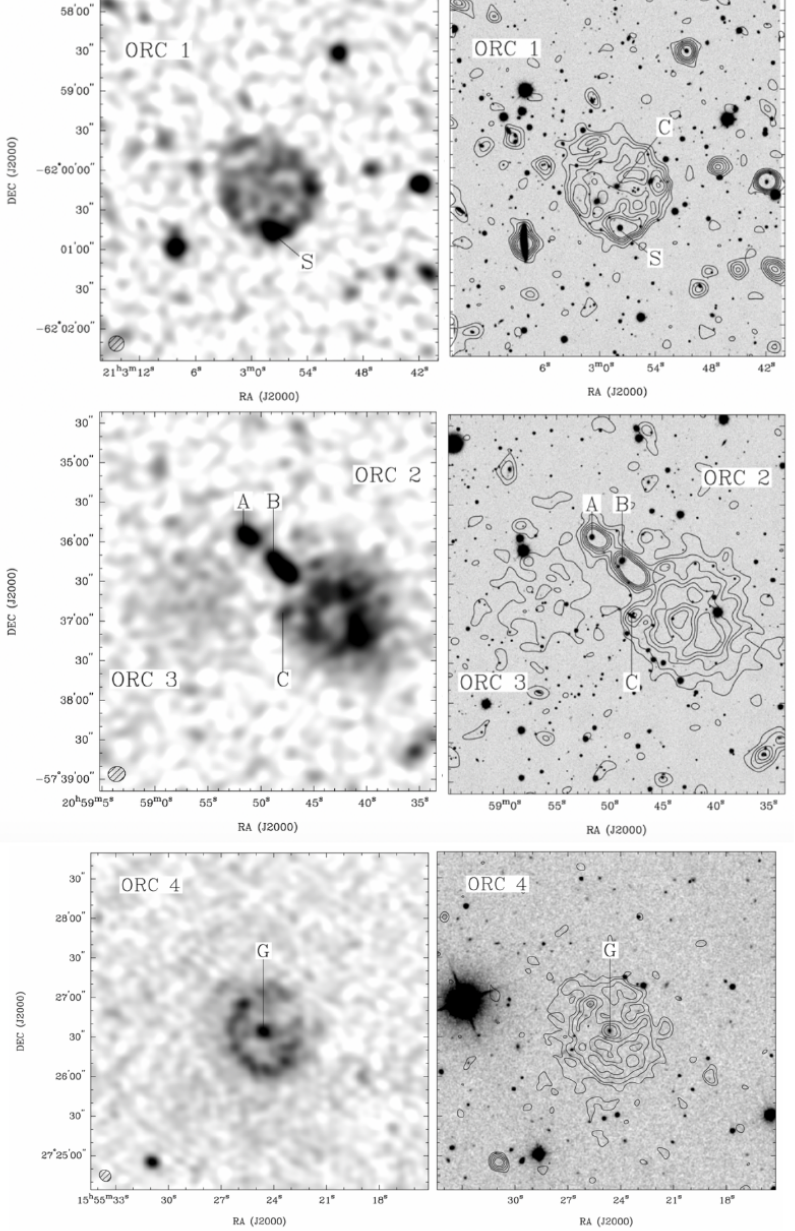
We have found an unexpected class of astronomical objects which have not previously been reported, in the Evolutionary Map of the Universe Pilot survey, using the Australian Square Kilometre Array Pathfinder telescope. The objects appear in radio images as circular edge-brightened discs about one arcmin diameter, and do not seem to correspond to any known type of object. We speculate that they may represent a spherical shock wave from an extra-galactic transient event, or the outflow, or a remnant, from a radio galaxy viewed end-on.

For brevity, and lacking an explanation for their origins, we dub these Objects "Odd Radio Circles",or ORCs.

These objects were discovered in the Pilot Survey[1] of the Evolutionary Map of the Universe (EMU)[2], which is an all-sky continuum survey using the newly-completed Australian Square Kilometre Array Pathfinder telescope (ASKAP)[3–5]. The EMU Pilot Survey (EMU-PS) used ASKAP to survey a field of about 270 deg^2 to an rms sensitivity of about 30 μJy/beam, with a spatial resolution of about 12 arcsec. Details of the observations and data reduction, and techniques used for data analysis, are given in the Supplementary Information.

Three ORCs (ORCs 1–3) were discovered by visual inspection of the images from the survey. Their rarity, together with their low surface brightness, makes it unlikely that they could have been discovered in previous radio surveys.

We discovered a further ORC (ORC 4) in archival data taken with the Giant MetreWave Radio Telescope (GMRT)[6] in March 2013. In most respects it is very similar to ORCs 1–3, but differs in having a central radio continuum source.

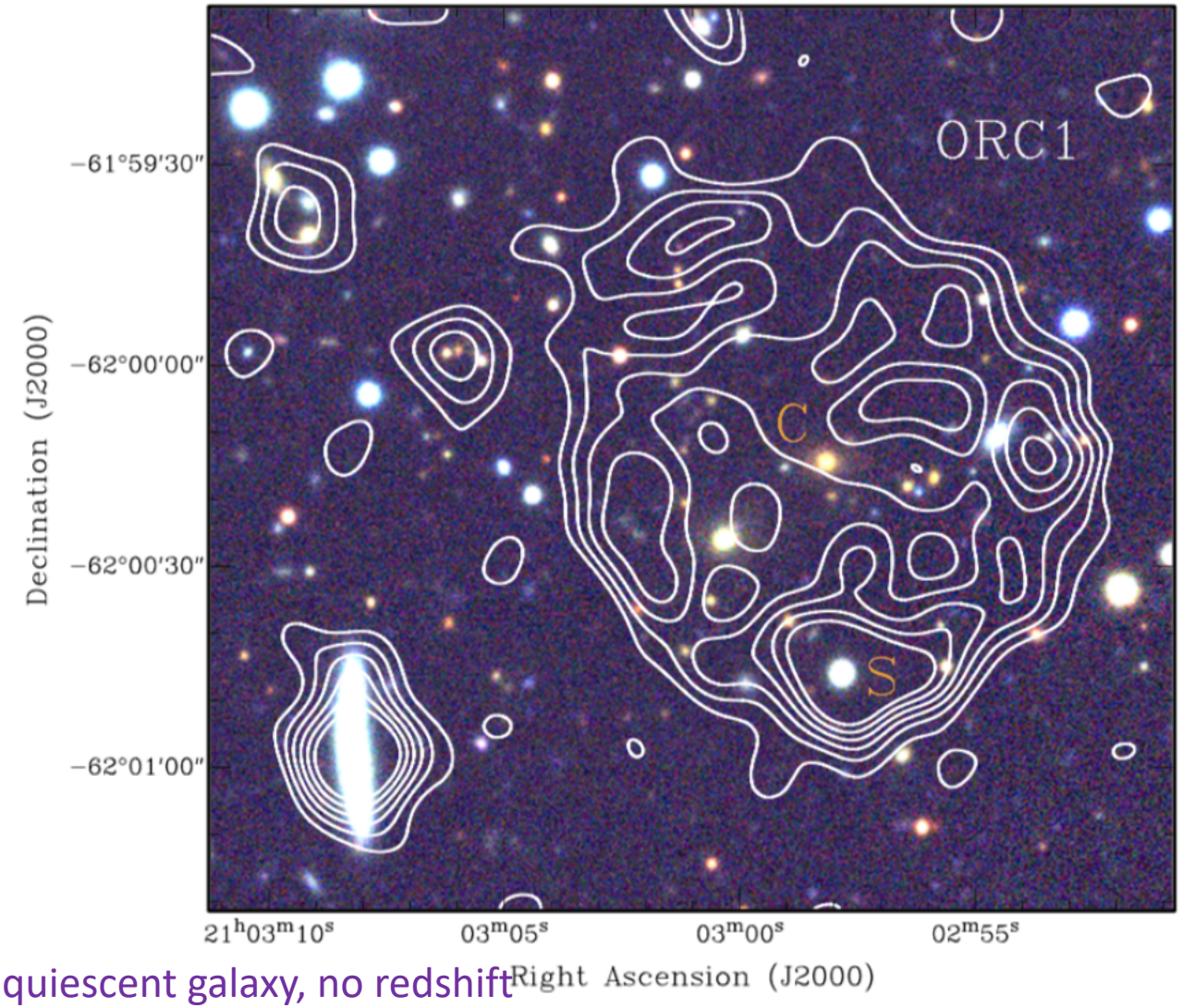


ASKAP 944 MHz

ASKAP 944 MHz

Gmrt 325 MHz

Figure 1: ASKAP radio continuum images at 944 MHz of ORCs 1–3 from the EMU Pilot Survey[1], and at 325 MHz of ORC 4 from GMRT archival data. On the left are greyscale images, with the synthesized beam shown in the bottom left corner, and radio contours overlaid onto DES optical images on the right, as described in the text. The contour levels for ORC 1 and ORC 2 are 45,



C- quiescent galaxy, no redshift

S – starburst galaxy, no redshift

Figure 3: ASKAP radio continuum image of ORC 1 (contours; see Fig. 1) overlaid onto a DES 3-color composite image; DES *gri*-bands are colored blue, green, and red, respectively. We identify two galaxies of interest: "C" lies near the centre of ORC 1 and "S" coincides with the southern radio peak (see Table 3).

На более высокой частоте – изображение слабее

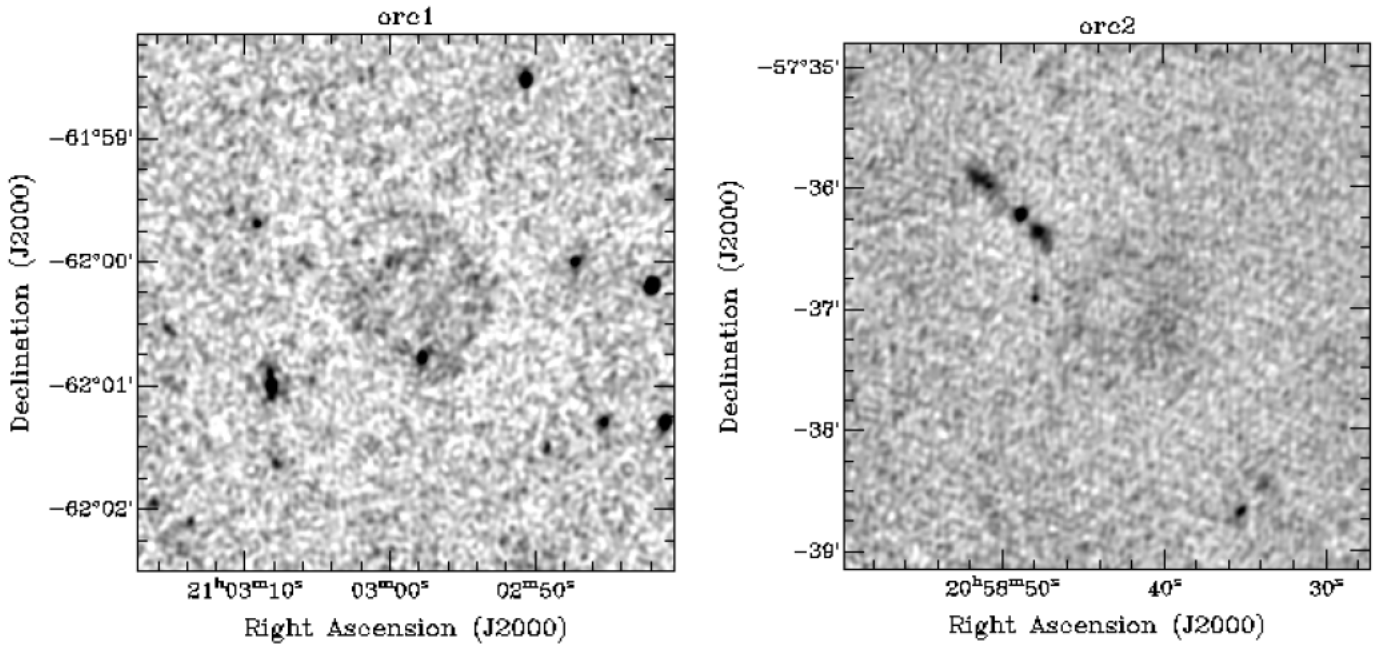


Figure 2: ATCA radio continuum images of ORCs 1–3 at a frequency of 2.1 GHz. The image rms is about 12 μJy/beam in both images. ORCs 1 and 2 are only faintly visible in these higher-frequency images, because of their steep spectral index and higher resolution, while ORC 3 is below the rms noise level. This image shows that sources A and B in ORC 2 are the two lobes of an FRI radio galaxy.

Two lobes
of radiogalaxy B?
Z=0.35 –
Случайная проекция?
C – ed-on galaxy
В центре кольца в оптике
ничего нет.

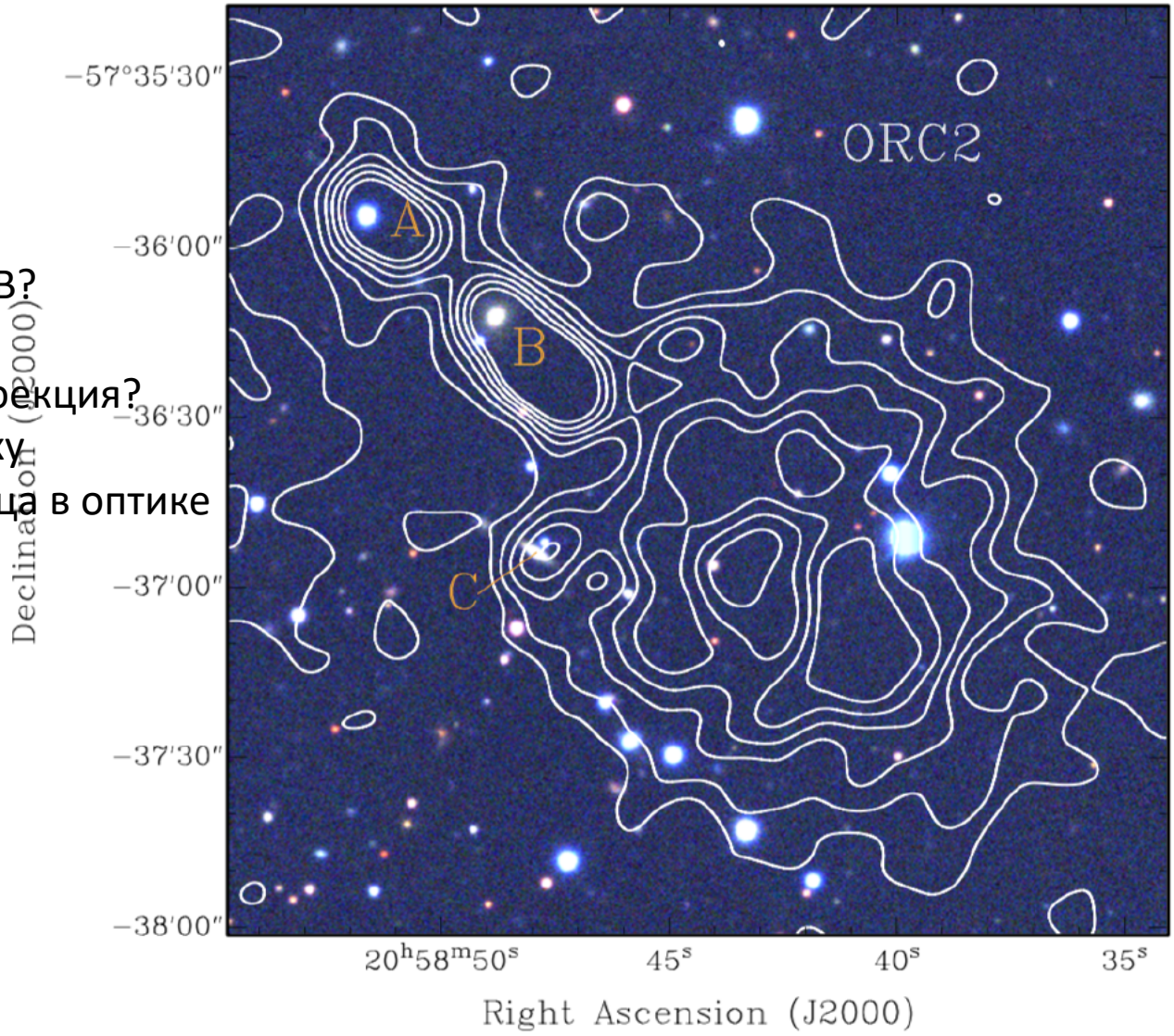
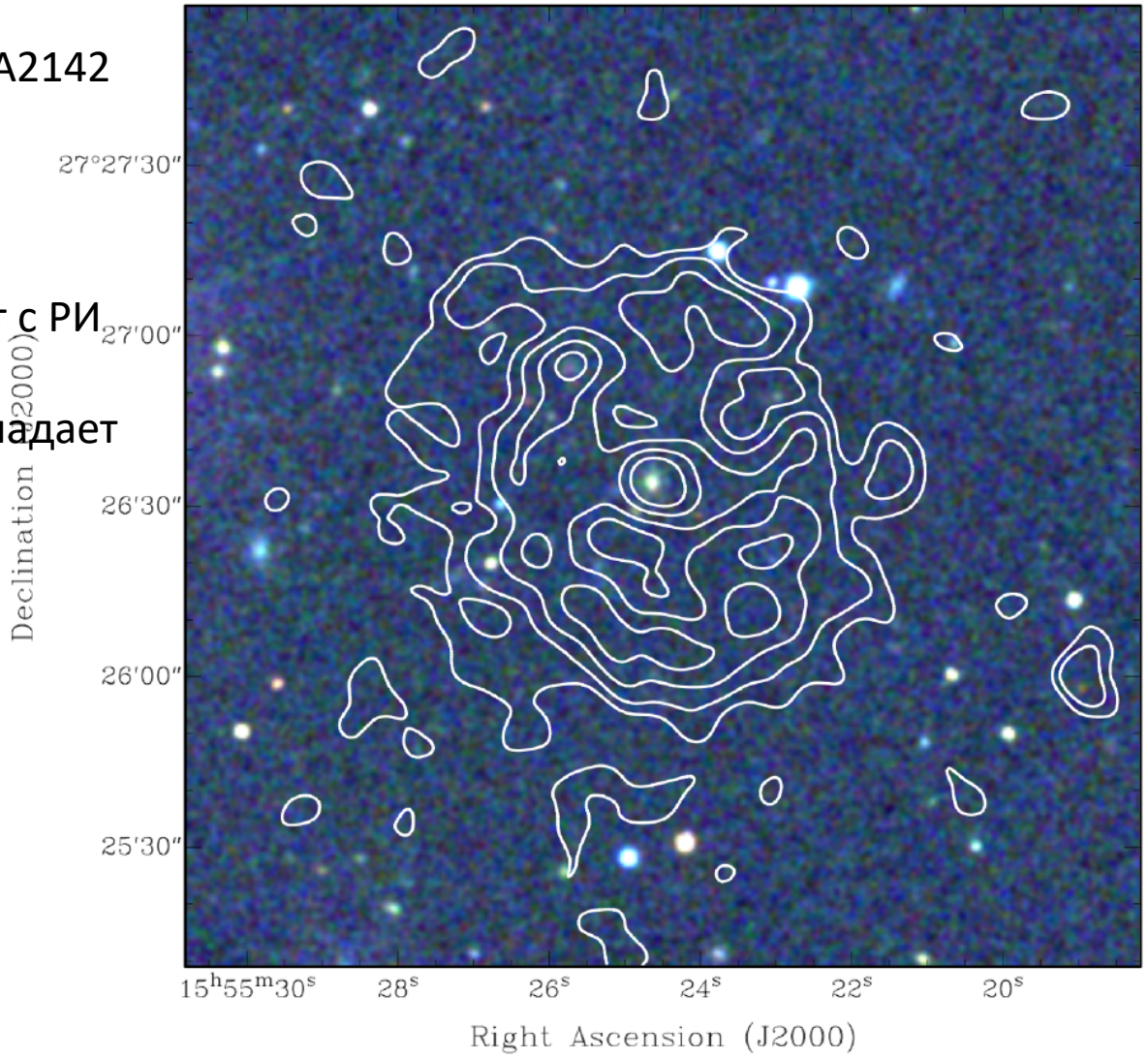


Figure 4: ASKAP radio continuum image of ORC 2 (contours; see Fig. 1) overlaid onto a DES 3-color composite image; DES *gri*-bands are colored blue, green, and red, respectively. We identify three sources of interest, annotated A, B and C (see Table 4).

Объект в скопрлении A2142

Единственный объект с РИ в центре.
Центральный РИ совпадает с галактикой
Z_{photom} = 0.39
Ring: 430x320Kpc



325MHz

Figure 5: GMRT radio continuum image of ORC 4 (contours; see Fig. 1) overlaid onto a SDSS 3-color composite image; SDSS *gri*-bands are colored blue, green, and red, respectively.

None of the ORCs has obvious optical, infrared, or X-ray counterparts to the diffuse emission, although in two cases there is an optical galaxy near the centre of the radio emission.

source	88 MHz	118 MHz	154 MHz	944 MHz	2121 MHz	α
ORC 1	105±16.5	69.5±8.6	38±6.0	6.26±1.25	2.29±0.23	–1.17±0.04
ORC 1(S)		.		0.60±0.12	0.15±0.03	–1.71±0.35
ORC 2	28±14.4	25±6.8	14±5.3	6.97±1.39	2.31±0.23	–0.80±0.08
ORC 2(A)				0.46±0.10	0.46±0.05	0.0±0.34
ORC 2(B)				0.76±0.15	0.66±0.07	–0.17±0.22
ORC 2(C)				0.19±0.05	0.07±0.03	–1.23±0.36
ORC 3			<5	1.86±0.37	<1.0	–0.50±0.20

source	150 MHz	325 MHz	1400 MHz	α
ORC 4	39±10	28±2.8	5.3±0.7	–0.92±0.18
ORC 4(G)		1.43±0.13		

Table 4: Properties of the optical/IR sources near ORCs 1–2

Source Name	ID	ASKAP	GALEX		DES					WISE					
		flux	FUV	NUV	g	r	i	z	Y	W1	W2	W3	W1–W2	z	Notes
		[mJy]	[mag]				[mag]				[mag]				
WISE J210258.15–620014.4	ORC 1 C	< 0.1	—	—	22.04	20.10	19.23	18.79	18.70	15.065	14.984	>12.939	0.081	??	
					0.06	0.01	0.01	0.02	0.04	±0.031	±0.061				
WISE J210257.88–620046.3	ORC 1 S	0.86	23.7	22.3	19.733	18.945	18.550	18.351	18.311	15.472	15.063	11.201	0.409	??	
			±1.2	±0.3	0.005	0.003	0.005	0.008	0.023	±0.034	±0.057	±0.138			
WISE J205851.65–573554.1	ORC 2 A	1.0	25.9	20.9	17.676	17.355	17.263	17.253	17.352	16.038	16.501	>12.716	–0.463	1.37	listed as a star in Gaia DR2
			4.0	0.1	0.001	0.001	0.001	0.002	0.01	±0.050	±0.252				
WISE J205848.80–573612.1	ORC 2 B	1.7	—	—	20.53	19.03	18.52	18.20	18.09	15.138	14.995	>12.431	0.143	0.35	2.5 arcsec extended spiral galaxy
					0.02	0.01	0.01	0.01	0.05	±0.035	±0.071				
WISE J205847.91–573653.8	ORC 2 C	0.2?	—	—	21.38	20.95	20.82	20.72	20.37	15.499	14.930	11.729	0.569		edge-on galaxy
					0.02	0.02	0.02	0.03	0.2	±0.041	±0.066	±0.232			

Table 5: Properties of the optical/IR source at the centre of ORC 4

Source Name	ID	GMRT	GALEX		SDSS					WISE					
		flux	FUV	NUV	u	g	r	i	z	W1	W2	W3	W1–W2	z	Notes
		[mJy]	[mag]				[mag]				[mag]				
WISE J155524.65+272633.7	G	1.15	—	—	22.61	21.18	19.64	19.00	18.40	14.847	15.119	12.341	–0.272	0.385	
SDSS J155524.63+272634.3		?			±0.70	±0.09	±0.03	±0.03	±0.06	±0.057	±0.112	±0.483	±0.126		

ORC properties

- The four ORCs discussed here are similar in displaying a strong circular symmetry. They are also similar in (a) having a diameter about 1 arcmin, (b) having a steep spectral index -1 (c) being at high Galactic latitude.
- They differ in that (a) two of them have a central galaxy while two do not, and (b) three of them (ORCs 1, 2 & 4) consist of a partly filled ring while one (ORC 3) seems to be a uniform disc.

Какова природа?

- If the ORCs are SNRs, which they strongly resemble, then this implies a population of SNRs in the Galaxy some 50 times larger than the currently accepted figure, or else a new class of SNR which has not previously been reported.

- The edge-brightening in some ORCs suggests that this circular image may represent a spherical object, which in turn suggests a spherical wave from some transient event. Several such classes of transient events, capable of producing a spherical shock wave, have recently been discovered, such as fast radio bursts , gamma-ray bursts, and neutron star mergers.

- However, because of the large angular size of the ORCs, any such transients would have taken place in the distant past.

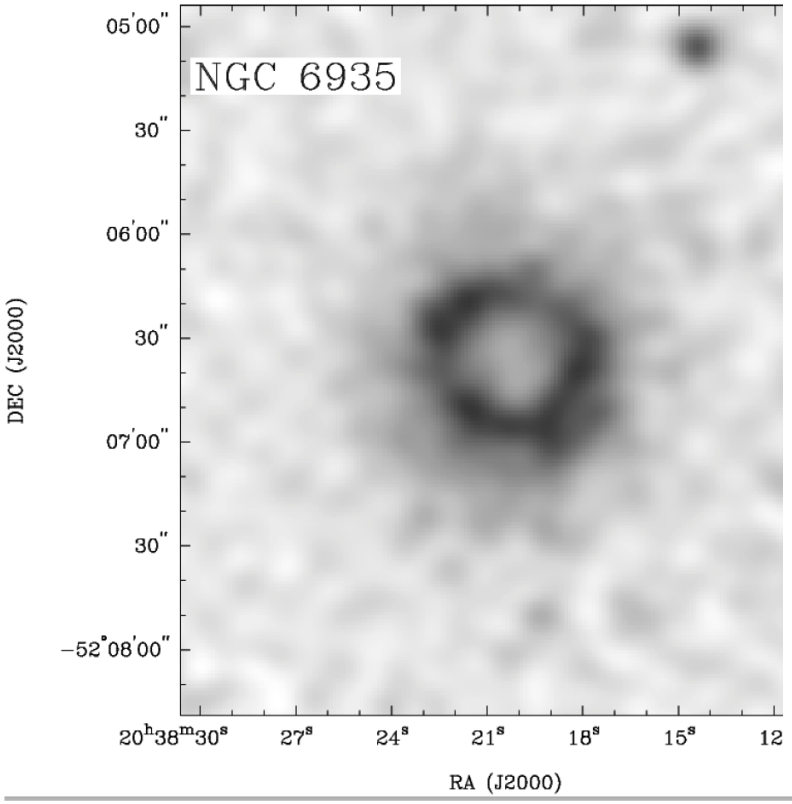


Figure 7: ASKAP 944 MHz radio continuum image of the face-on, star-forming galaxy NGC 6935 (v = 4543 km s^{-1}), as observed in the EMU-PS.

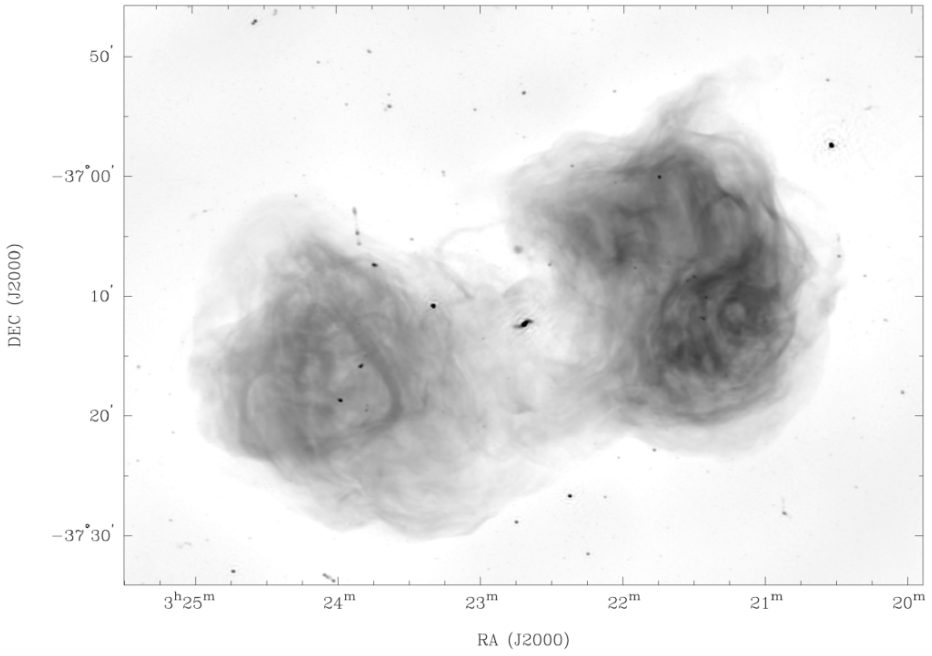


Figure 8: ASKAP 944 MHz radio continuum image of the double-lobe radio galaxy Fornax A, from unpublished ASKAP data.

Возможные варианты?

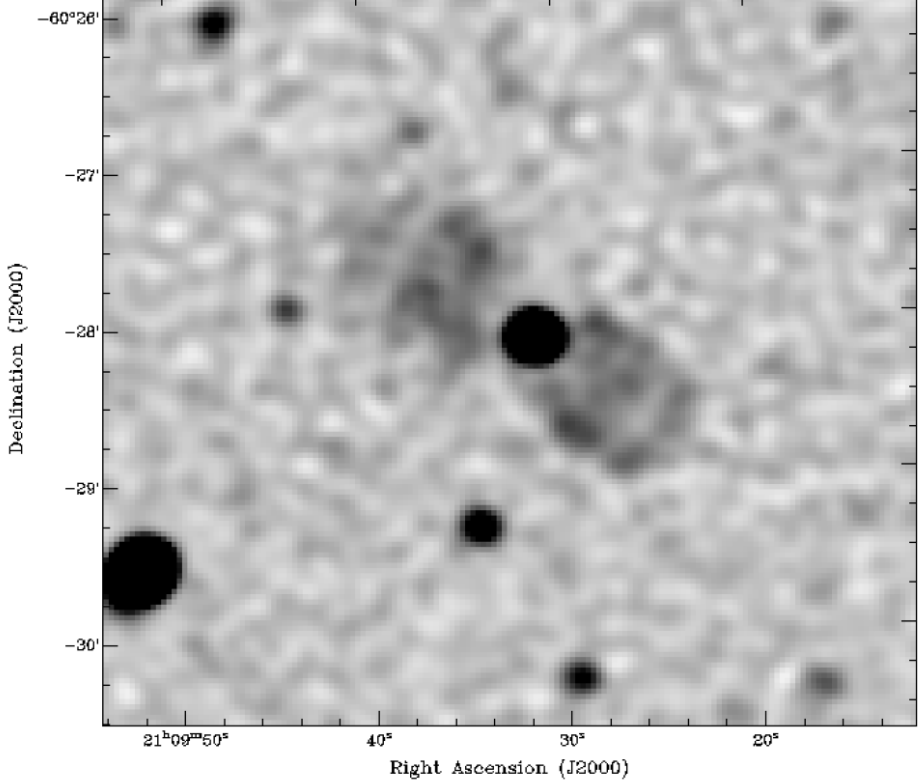


Figure 9: EMU-PS image of the edge-brightened double-lobe radio galaxy EMU PD J2109:31.3-602806

Возможные варианты?

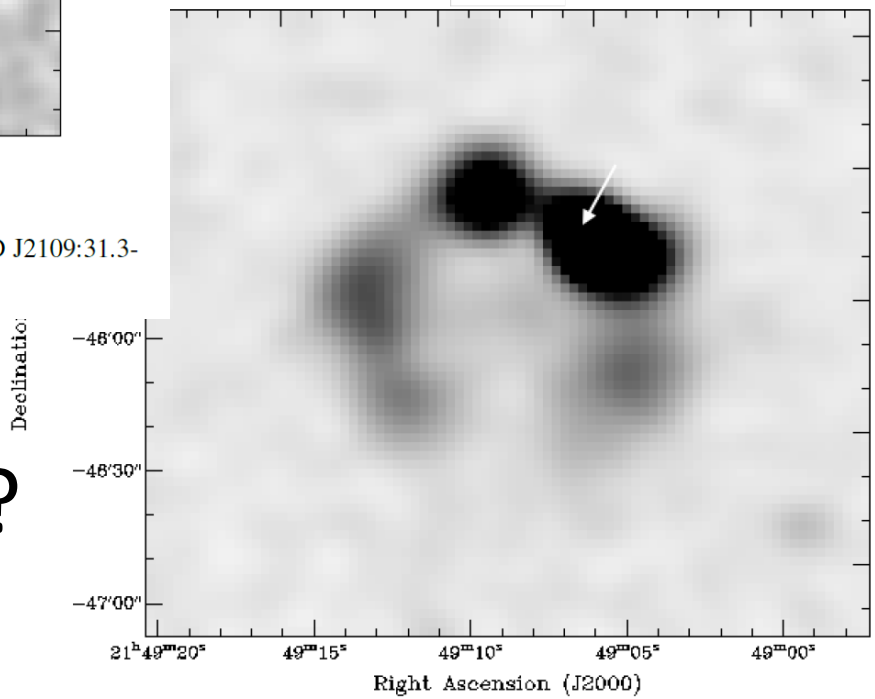


Figure 10: EMU-PS image of the bent-tail radio galaxy EMU PD J214905.4-614542. The position of the host galaxy is indicated by an arrow.

Возможные варианты?

- Supernova Remnant
- Galactic Planetary Nebula
- Face-on star-forming galaxy or ring galaxy
- Lobe from a double-lobed radio galaxy, viewed side-on
- Lobe from a double-lobed radio galaxy, viewed end-on
- A bent-tail radio galaxy
- Einstein Ring
- Ring around Wolf-Rayet star
- Cluster halo
- Galactic Wind Termination Shock

- The termination shock associated with a star-forming galaxy should be easily capable of accelerating CR electrons to the few 10 GeV energies at which they would produce synchrotron radiation at 1 GHz.

Выводы

- The ORCs represent a new type of object found in radioastronomy images.
- We also acknowledge the possibility that the ORCs may represent more than one phenomenon, and that they have been discovered simultaneously because they match the characteristics of the ASKAP observations, which occupy a part of the observational parameter space which has hitherto been poorly studied.
- Further work is continuing to investigate the nature of these objects.