**The search for radio emission from exoplanets using LOFAR beam-formed observations: Jupiter as an exoplanet.**

[**https://ui.adsabs.harvard.edu/abs/2019A%26A...624A..40T/abstract**](https://ui.adsabs.harvard.edu/abs/2019A%26A...624A..40T/abstract)

* Detection of planetary auroral radio emission likely sole method of detecting B-fields from exoplanets without doubt
* No confirmed radio emission has been detected yet, despite number of observations recently (and theoretical studies)
* Some astronomers have tried to estimate the expected radio flux density – with large uncertainties 🡪 BUT this helps to see if it detections could realistically be made with current radio telescopes and technology
* Most recent estimates of emission f compatible with some radio telescopes, and estimated flux densities theoretically possible with current equipment sensitivities
* Two main types of observation of exoplanets with low-frequency radio telescopes: imaging and beam-formed observations:
  + Imaging observations (interferometric) are more robust against RFI and bad data can be excluded (but are computationally expensive)
  + Beam-formed observations have higher time resolution 🡪 can localise and remove some RFI more precisely (short/sporadic), good for detection of short signals/bursts but cannot reliably detect continuous/slow-varying signals, less computationally expensive than imaging observations
  + For both methods, hard to find min detectable flux density if signal is “bursty”
* Idea behind paper: create artificial dataset of “Jupiter as an exoplanet” by scaling its radio emission to mimic exoplanet radio emission 🡪 define set of observables to create guideline in the search for exoplanetary radio emission and measure sensitivity limit of LOFAR (beam-formed observations)
* Assuming that radio emission from exoplanet similar to Jupiter’s, searching over range of timescales with Q1a (time series) and Q4f helpful for detection
* Found that detection limits don’t depend on where in the sky the observations are pointed at (provided conditions of observation were good enough)
* Probability of false positive obtaining a signal similar to Jupiter is 1.4x10-5 for Stokes V and 3.2x10-4 for Stokes I 🡪 i.e. statistically significant for these parameters. (when compared to observations with no astrophysical signal with two OFF beams, false positive rates are 99% for Stokes I and 20% for Stokes V 🡪 these observations classified as non-detections).
* Estimated flux density from 50-60 MHz for Stokes V Q1a (time series observable) is higher than the expected sensitivity of LOFAR beam-formed observations
* Stokes I sensitivity also above theoretical sensitivity ? (p. 13)
* Both Q1a and Q4f are above theoretical sensitivity of LOFAR – BUT are complementary observables and should be used together (since they investigate different emission structures and timescales).
* These complex observables allow astronomers to detect a signal more confidently and distinguish it from false positives (otherwise, would require higher level of confidence to be considered reliable).
* Therefore, find that it is possible to detect an exoplanetary polarised signal stronger than Jupiter’s emission strength (105times stronger, at distance of 5pc)
* Rapidly rotating planets with strong internal plasma sources also thought to produce radio emission at detectable levels (several AU from host star)
* Expected radio flux is a function of the exoplanetary host star 🡪 stronger radio signals expected for planets around young stars, and planets with regular and powerful coronal mass ejections
* Planetary emission expected to be much stronger than stellar emission, but would still have to confirm that the signal is produced by the exoplanet and not the host star (e.g. detection of radio emission from transiting planet, with planetary emission disappearing during secondary eclipses)
* Extra data that would help with the radio signal interpretation: stellar light curves, stellar magnetic field maps, stellar rotation rate, data on stellar wind, stellar age estimate, exoplanet’s orbital inclination
* Conclusions:
* Pipeline for beam-formed LOFAR Stokes V data should detect signals of a Jupiter-like planet at 13 000 AU, or exoplanet with 105 times mean radio flux of Jupiter strong burst emission
* Exoplanets suggested to be possible to detect from: 55 Cnc (12 pc), Tau Bootis (16 pc), Upsilon Andromedae (13 pc) if emission strong enough
* Stokes V pipeline achieves 1.3 times theoretical sensitivity of LOFAR
* SKA will be even more sensitive (by factor of 30)

**Limits on low-frequency radio emission from southern exoplanets with the Murchison Widefield Array**

[**https://ui.adsabs.harvard.edu/abs/2015MNRAS.446.2560M/abstract**](https://ui.adsabs.harvard.edu/abs/2015MNRAS.446.2560M/abstract)

* Sample including 13 planetary systems not previously targeted with radio observations
* No radio emission detected at 154 MHz, but 3 sigma upper limits placed on the range (15.2-112.5 mJy)
* Searched for circularly polarised emission but no detections made 🡪 3-sigma upper limits made in 3.4-49.9 mJy range 🡪 comparable with best low-frequency radio limits in current literature 🡪 convert to luminosity limits between 1.2x1014-1.4x1017 W (if emission assumed 100% circularly polarised)
* Expected that magnetised extrasolar planets emit strongly in the radio region – similar to magnetised planets in the solar system
* Intense emission can be produced by electron-cyclotron maser instability if planet has intrinsic magnetic field and source of energetic electrons 🡪 sporadic emission, with variable timescales (seconds to days)
* In radio region, radiation from planets comparable strength to parent star (e.g. Jupiter)
* Strongest exoplanetary emission expected to be from more massive planets than Jupiter (if orbit host star at short orbital distances)
* Most exoplanets discovered up to now through indirect means (e.g. radial velocity, transit searches)
* Small number have been found using direct imaging 🡪 radio observations are another method of direct detection
* Radio observations of exoplanet would allow us to see if the planet has a magnetic field, and place limits on its strength near the planet’s surface 🡪 detection of circular polarisation would confirm which magnetic hemisphere the emission is from and hence, limit on plasma density in the magnetosphere.
* Number of recent attempts to detect radio emission from known exoplanets
* Possible detection of HAT-P-11b (Neptune-mass exoplanet) with GMRT in 2013 🡪 but detection not confirmed in follow-up observations
* Largest radio survey so far was in 2014 with TIFR GMRT Sky Survey 🡪 no detections made, but 150 MHz 3-sigma upper limits of 8.7-136 mJy put on 171 planetary systems
* Cyclotron maser emission is 100% circularly polarised 🡪 planets should be able to be detected with circular polarisation (Stokes V) at levels close to their total intensity
* Exoplanetary radio emission expected to peak at frequencies below 10-100 MHz 🡪 not detectable with most telescopes
* Key assumptions of this paper: circularly polarised radio emission is a large fraction of the total intensity (🡪 can calculate luminosity limits BUT ignores likely time variability of exoplanetary radio emission)
* SEE PAPER for technical details about observation calibrations
* No radio sources detected at positions of any system considered
* Maximum emission frequency of cyclotron maser emission is at the electron gyrofrequency and proportional to the maximum planetary magnetic field strength
* To be detected at 154 MHz, an exoplanet would need a magnetic field strength 4 times that of Jupiter 🡪 i.e. young, giant, extrasolar planets of 5-10 Jupiter masses
* The sample of 17 exoplanets included 13 that had not previously been targeted with radio observations
* No detections of radio emission at 154 MHz: upper limits of 15.2-112/5 mJy made on this emission
* No detections of circularly polarised emission: upper limits of 3.4-94.9 mJy
* Possible reasons why no detections made: more sensitive observations needed (since only best limits place any constraints on predicted flux densities), observing frequency still too high compared to predicted maximum emission frequency for many systems in sample
* Instrumental limitations will be reduced with future telescopes 🡪 SKA in particular
* Also, need observations with better coverage of planetary orbital period – since exoplanetary radio emissions likely to be orbitally beamed 🡪 full coverage of planetary orbital period would allow stricter limit on emission
* Since axis of beaming unknown, necessary to target range of known exoplanets
* Emission is likely time variable, and modulated by the orbital frequency 🡪 constant monitoring of large number of exoplanetary systems would be ideal
* Development of SKA 1-Low will allow exoplanets to be detected at low frequencies, and blind surveys to potentially find new exoplanetary systems through radio emission

**The search for radio emission from the exoplanetary systems 55 Cancri, u Andromedae, and T Bootis using LOFAR beam-formed observations**

<https://ui.adsabs.harvard.edu/abs/2021A%26A...645A..59T/abstract>

* circularly polarised bursty emission from tal Bootis system in range 14-21 MHz (tentatively) detected with flux density of 890 mJy, as well as slowly variable circularly polarised emission from tal Bootis at 21-30 MHz with flux density 400 mJy
* assuming detected signals are real, source is likely the tal Bootis planetary system (possible mechanism is cyclotron maser) 🡪 limits for planetary polar surface magnetic field strength which are compatible with theoretical predictions
* **Searching for Stellar and Planetary Emission in Large Field-of-view Radio Sky Surveys**

[**https://ui.adsabs.harvard.edu/abs/2022ApJ...926..228L/abstract**](https://ui.adsabs.harvard.edu/abs/2022ApJ...926..228L/abstract)

* detection of low-f radio emission from stellar and exoplanetary systems allows greater knowledge of stellar activity, extrasolar space weather and planetary magnetic fields
* redetection of 5 stars
* Radio emission observed at the position of a brown dwarf star, but follow-up study with higher angular resolution needed to see if radio emission is from the brown dwarf or other background object (high astrometric uncertainty)
* All chosen radio sources are located in nearby star-forming regions
* Observational constraints calculated for future large-scale searches – upper limits on average quiescent radio luminosity of object families chosen for investigation
* theory predicts that detection thresholds for radio emission due to plasmas interacting with planetary magnetic fields has almost been reached
* stars produce low-f radio emission, most commonly through thermal free-free mechanism
* other more active stars than our sun (e.g. young stars and M dwarfs), can produce flares and CMEs (coronal mass ejection) more strongly and often 🡪 high energy particles produced can lead to planetary radio emissions as well
* primary low-f emission mechanism observed for brown dwarfs (which have substellar-mass) appears to be the same as the predicted radio emission mechanism for planets
* planets in our solar system (e.g. Jupiter) have been observed to emit low-f radio emissions
* cyclotron maser instability (CMI) process that produces Jupiter’s strongest low-f radio emission: input charged particles provide energetic electrons which become trapped and gyrate about magnetic field lines, producing radio emissions. In the solar system, solar wind is typical source of electrons (or stream of particles from Io for Jupiter)
* observations of low-f radio emission from CMI provides lots of information about exoplanetary magnetic fields 🡪 implications for habitability of exoplanets – presence of magnetic field around planet could shield it from high-E particles and atmospheric stripping from active host stars (e.g. young stars and M dwarfs)
* could also help to characterize exoplanets and even provide info about planet formation
* recent tentative detection of planetary induced CMI radio emission with LOFAR (high circular polarisation, temporal variability 🡪 could be caused by planet-star interaction like Jupiter-Io system)
* sample of known exoplanets was constrained to <300pc away and within field of view of the radio sky surveys 🡪 around 850 planetary systems identified (chosen distance due to inverse square law relation for flux with distance)
* if planetary radio emission is found to exist, this paper predicts that radiation environments and hence emission mechanisms between the different types of planets (e.g. hot Jupiters and super-Earths) could be quite different 🡪 hot Jupiters could be magnetically connected to host stars and induce CMI on star itself, but further out planets likely would depend only on charged particles from stellar wind
* 6 possible detections, but follow-ups needed (four are low or intermediate-mass YSOs, 1 is young but evolved massive star in a star-forming association, 1 at position of young brown dwarf candidate)
* Image stacking technique SEE PAGE 11
* Higher detection rate of YSOs could be due to fact that pre-main-sequence stars have high levels of magnetic activity (due to enhanced rotation and deep convective layers, and accretion from disk could produce flare-like events)
* Observations of brown dwarfs at low radio frequencies constrains their magnetic field properties and mechanisms 🡪 hence reveal more about how planetary magnetic fields are generated (since brown dwarfs similar to massive planets)
* Large different in intrinsic luminosity among brown dwarf radio emitters: could be due to differences in plasmas 🡪 M-type more active than L-type brown dwarfs
* Radio emission detected not conclusively associated with exoplanets but some upper limits on radio flux calculated
* Models to predict exoplanetary radio emission with estimates of planetary magnetic moments and stellar winds:
  + Kinetic energy model: input radio power dominated by kinetic energy flux of stellar winds
  + Magnetic energy model: magnetic energy flux of interplanetary magnetic field determines output power
  + CME model: CMEs are main driver of emission
  + Unipolar interaction model: unmagnetized planet provides energetic particles to create emission closer to stellar surface (like larger version of Jupiter-Io system)
  + THIS PAPER favours the magnetic energy model and uses it to make predictions
* Magnetic energy model predictions/calculations: predicts that no planets emit at frequencies >400 MHz, 77.5% of the planets would have peak emission frequencies <70 MHz, 23% would peak at frequencies <10 MHz (below ionospheric cutoff) 🡪 would need observations from space to detect <10 MHz
* Based on this model, only small proportion of chosen exoplanet sample would emit at frequencies covered by observations
* YSOs (young stellar objects) much more likely to produce observable radio emission than other populations (e.g. field stars or mature exoplanet-hosting systems)

**Coherent radio emission from a quiescent red dwarf indicative of star-planet interaction**

[**https://ui.adsabs.harvard.edu/abs/2020NatAs...4..577V/abstract**](https://ui.adsabs.harvard.edu/abs/2020NatAs...4..577V/abstract)

* Detected low-frequency radio emission from a quiescent star of red dwarf/M spectral class (most common stellar type)
* The emission is similar to planetary auroral emission in characteristics 🡪 coronal structure dominated by global magnetosphere with low plasma density
* Emission properties consistent with theoretical predictions for interaction with Earth-size planet in 1-5 day-long orbit

**The detectability of radio emission from exoplanets**

[**https://ui.adsabs.harvard.edu/abs/2018MNRAS.478.1763L/abstract**](https://ui.adsabs.harvard.edu/abs/2018MNRAS.478.1763L/abstract)

* Magnetised exoplanets should emit strongly in the radio region
* Radio emission directly traces the planetary magnetic fields 🡪 can place constraints on the physical parameters of these
* Large comparative studies of predicted radio emission characteristics for known exoplanet population can help identify physical parameters responsible
* Set of exoplanets predicted to produce observable radio emission: Hot Jupiters orbiting young stars 🡪 young systems predict strong stellar magnetic fields and/or dense winds 🡪 key for producing bright, observable radio emission
* Over 3700 exoplanetary systems have been discovered
* Direct imaging difficult since there is large contrast between optical/infrared brightness of exoplanets and their host stars 🡪 majority of known population discovered indirectly
* Alternative method: direct detection of magnetised exoplanets through radio observations (since expected radio emission of planets could exceed host star emission)
* Radio observations also allow direct measurement of planet’s surface magnetic field strength and hence insight into interior composition of planet
* Variability of the radio emission in time and frequency can help place constraints on the rotational period of the planet, the orbital period and inclination, and the magnetic field tilt relative to rotation axis.
* Magnetised planets in our solar system have been found to emit intense, low-f radio emission from auroral regions through electron-cyclotron maser instability (CMI)
* Observed emission is highly circularly/elliptically polarised, beamed and varies on timescales from seconds to days
* The radio emission is produced from the propagation of energetic (keV) electrons along converging magnetic field lines in the planet’s magnetosphere
* In similar way, magnetised exoplanets expected to emit intense, low-f radio emission
* Can predict intensity of radio emission from an exoplanet using the Radiometric Bode’s Law (RBL) (relates incident energy flux of stellar wind to radio power produced by planet) BUT relationship between stellar wind and planetary auroral radio emission might not be as direct in large, corotating magnetospheres as for Jupiter
* According to estimates using the RBL, Hot Jupiters located in more exotic planetary environments (e.g. around pre-main sequency stars or stars evolved off main-sequence)
* However, another theoretical prediction is that radio emission from some exoplanets dominated by another mechanism (magnetosphere-ionosphere coupling current system) linked to internal plasma source (e.g. active moon) 🡪 radio emission not predicted by RBL: instead, fast rotating massive planets orbiting in large orbits around stars with bright emission in X-UV could create observable/detectable radio emission
* Also other arguments against the RBL – specifically, for close-in planets
* 3 different types of interaction between planetary obstacle and ambient stellar wind that cause radio emission
* Star-planet interaction: SEE PAGE 1764
* Stellar-wind model (Parker stellar wind model)
* Planetary magnetosphere: need to estimate planet’s magnetic field strength at surface to be able to predict max emission frequency of radio emission
* Required physical quantities for calculating expected radio flux density or emission frequency – mass of exoplanet and star, distance to the exoplanet system, semi-major axis of exoplanet orbit and the age of the star
* MWA: sensitivity of the instrument is greater in circular polarisation than in total intensity 🡪 exoplanets (which should have highly circularly polarised emission) good candidates for the telescope
* SEE GRAPH on p. 1771
* MWA upper limits on luminosity within frequency range 169-230 MHz (important because there is an expected sharp cutoff in emission frequency)
* Expected radio flux density decreases with the associated max emission frequency 🡪 deficient number of Jupiter or larger-size planets orbiting host stars at small radii
* Brightest emission predicted for Hot Jupiters orbiting young (<=2.5Gyr)
* Beaming of the emission could explain non-detections (unknown whether there is an optimal orbital phase within expected emission could be detected) 🡪 need observations that cover the full orbit of young Hot Jupiter systems