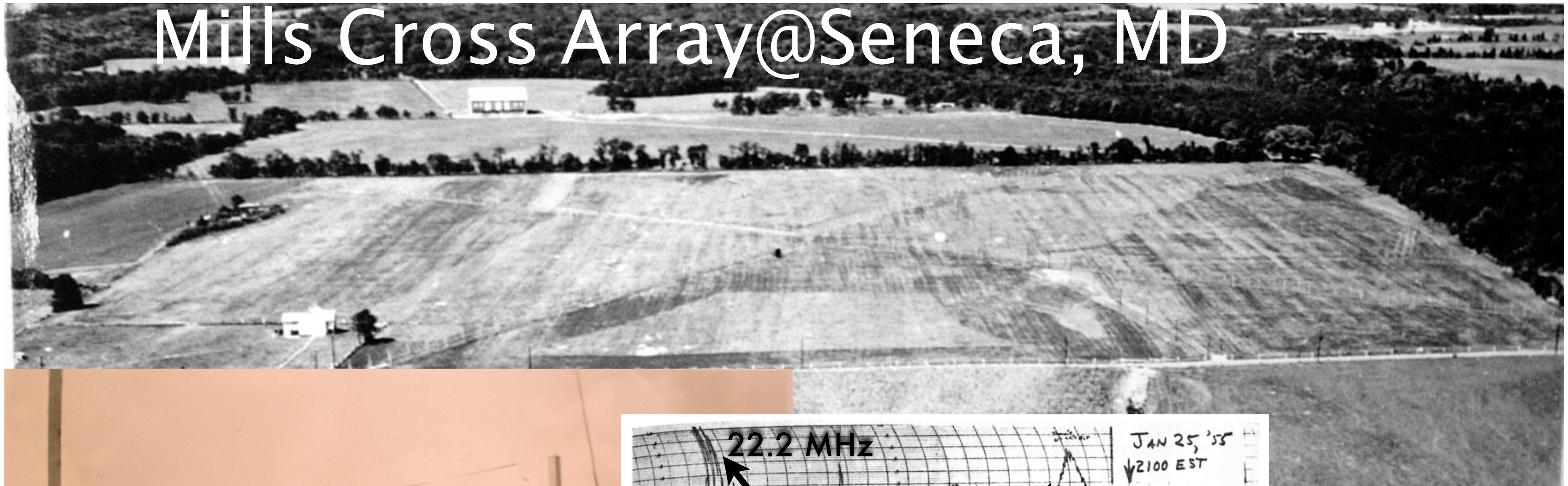
Probing Jupiter's auroral radio sources with Juno

Science at Low Frequencies IV, Sydney, Australia
December 15, 2017

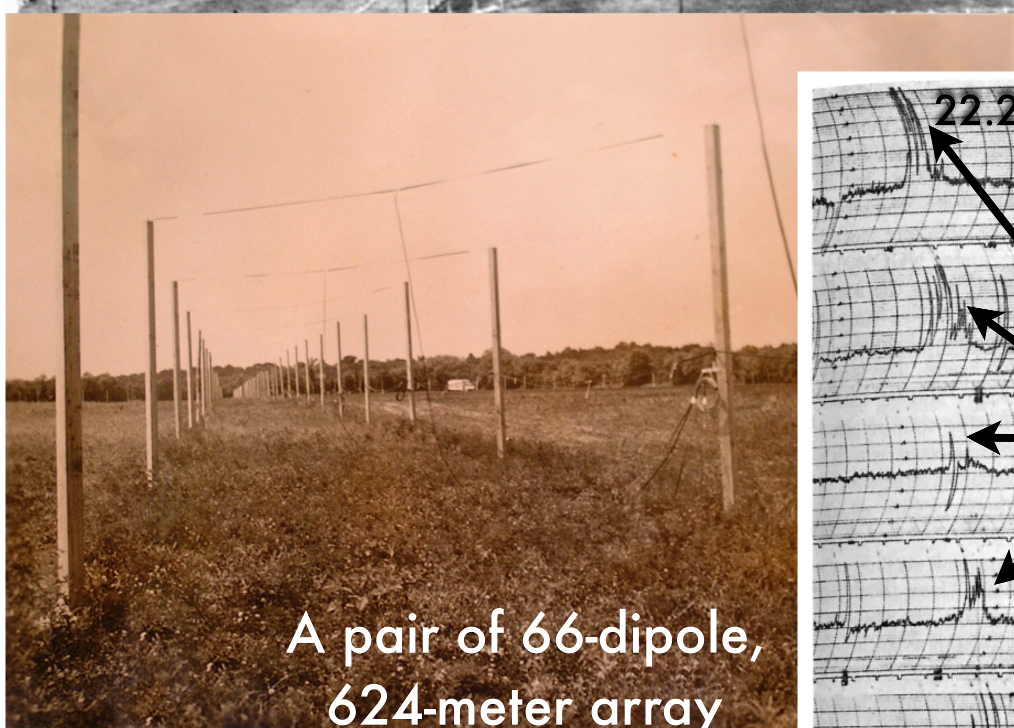
Masafumi Imai (University of Iowa)

In Collaboration with:
W.S. Kurth, G.B. Hospodarsky, G.R. Gladstone, T.K. Greathouse, B. Bonfond, D. Grodent, P. Louarn, S.J. Bolton, J.E.P. Connerney, S.M. Levin, A. Lecacheux, L. Lamy, P. Zarka, T.E. Clarke, and C.A. Higgins

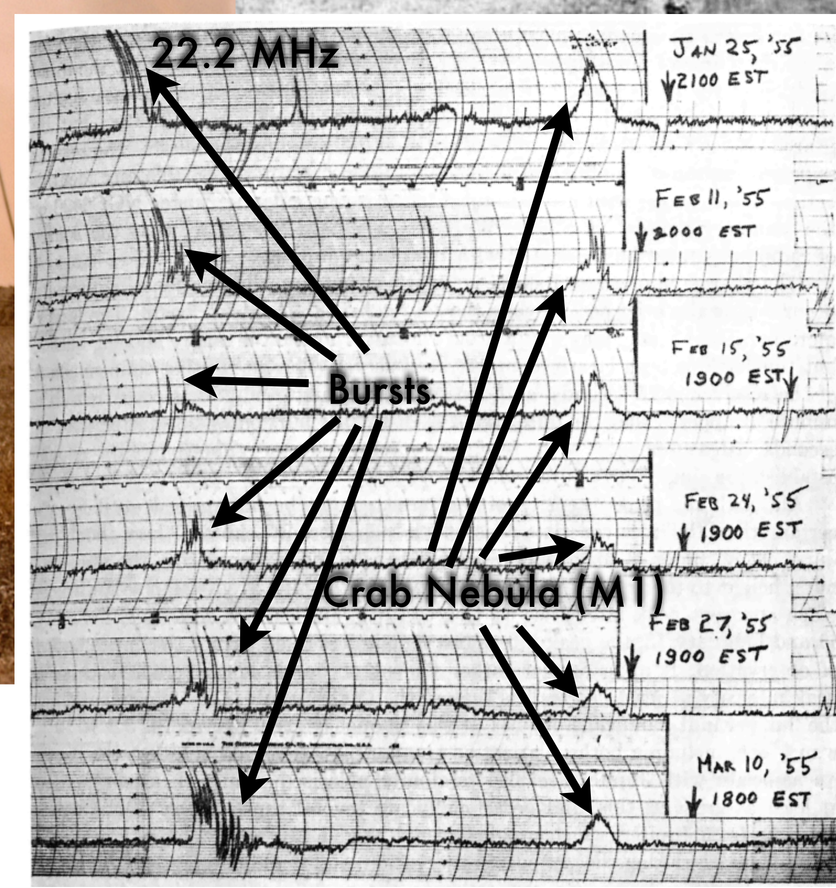
Serendipitous discovery of Jupiter's auroral radio emissions

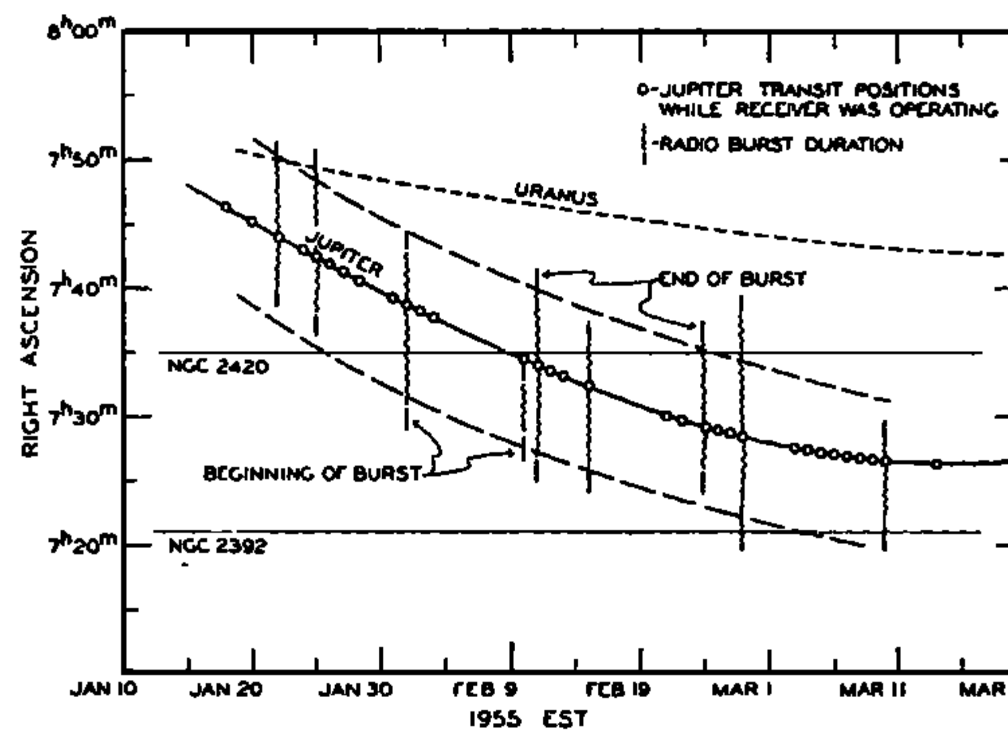


In 1955, Burke & Franklin accidentally discovered Jovian radio emissions from Mills Cross Array.



[Garcia+, 2005]

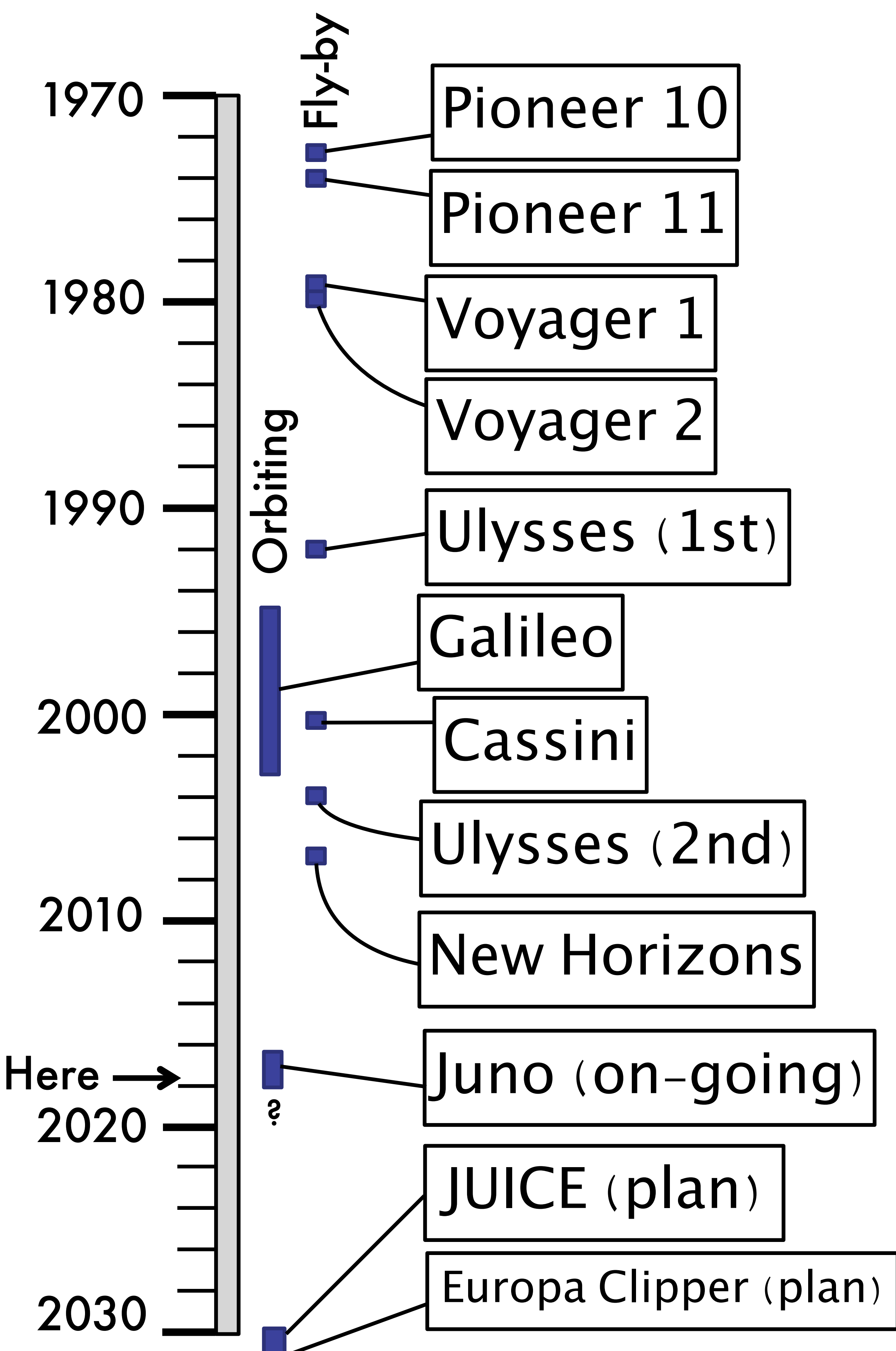


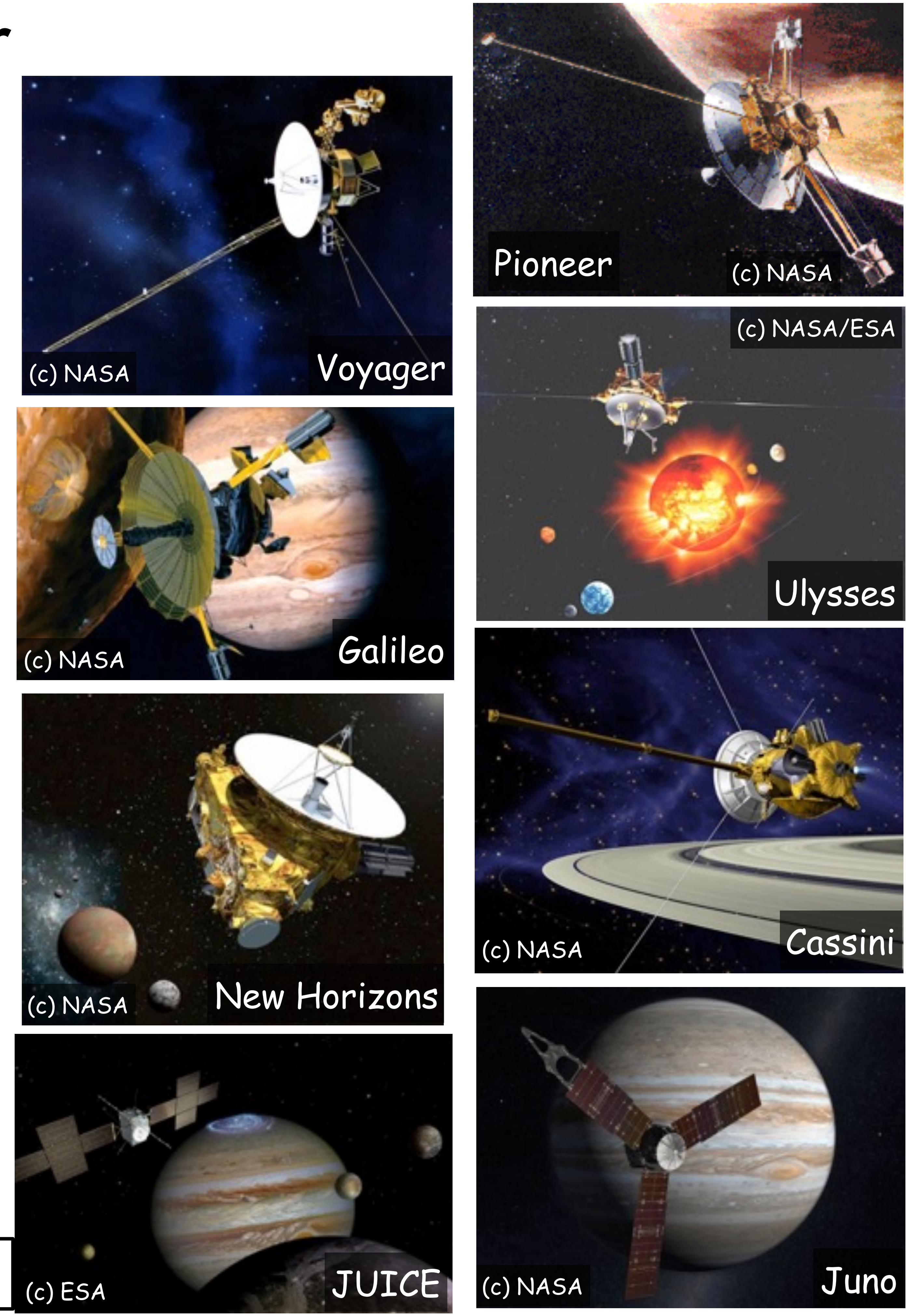


[Burke&Franklin, 1955]

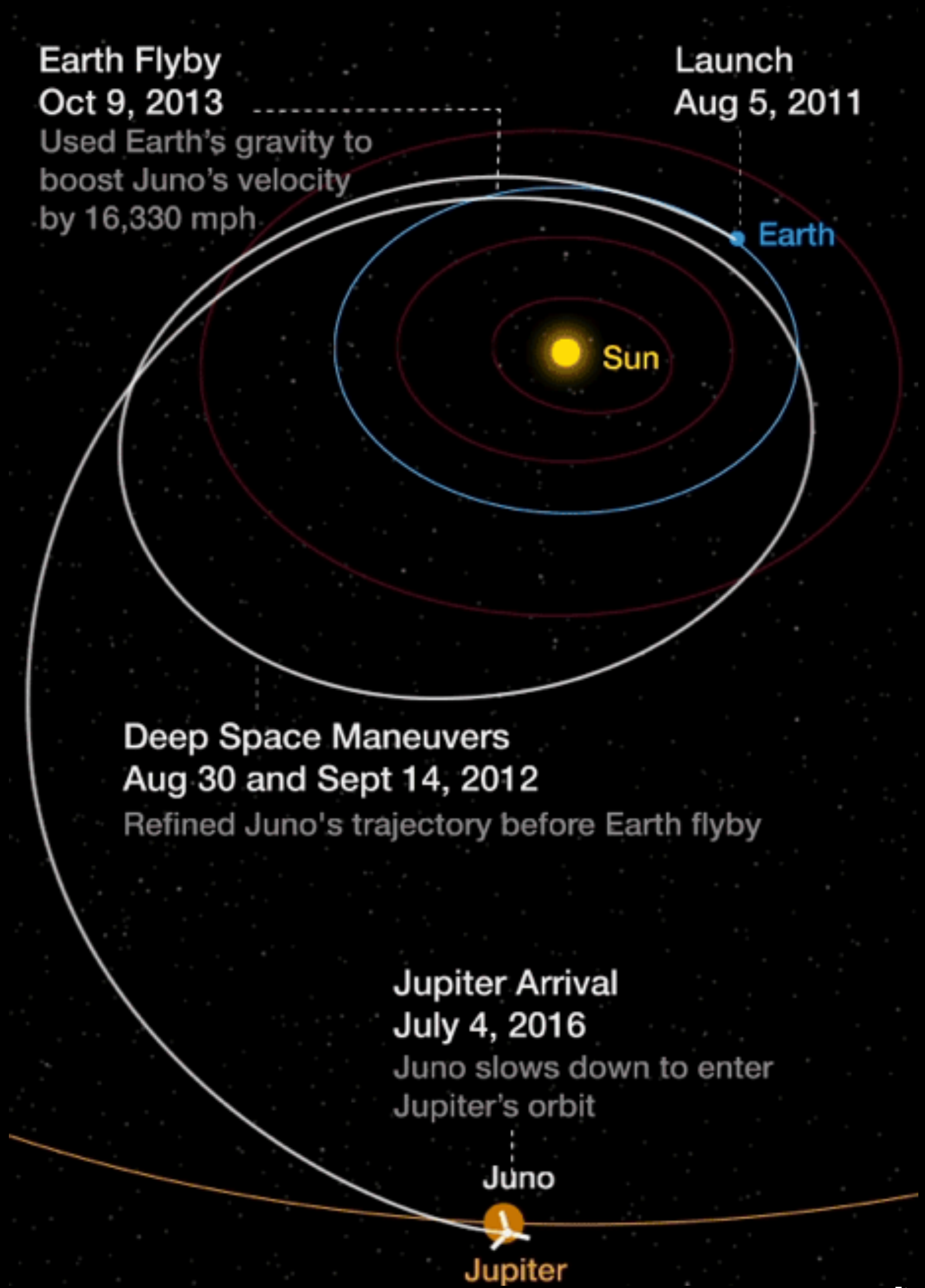
Since this serendipitous discovery, the study of planetary magnetospheres in our solar system has started!

Spacecraft at Jupiter





NASA's Juno Mission to Jupiter



[NASA/JPL]

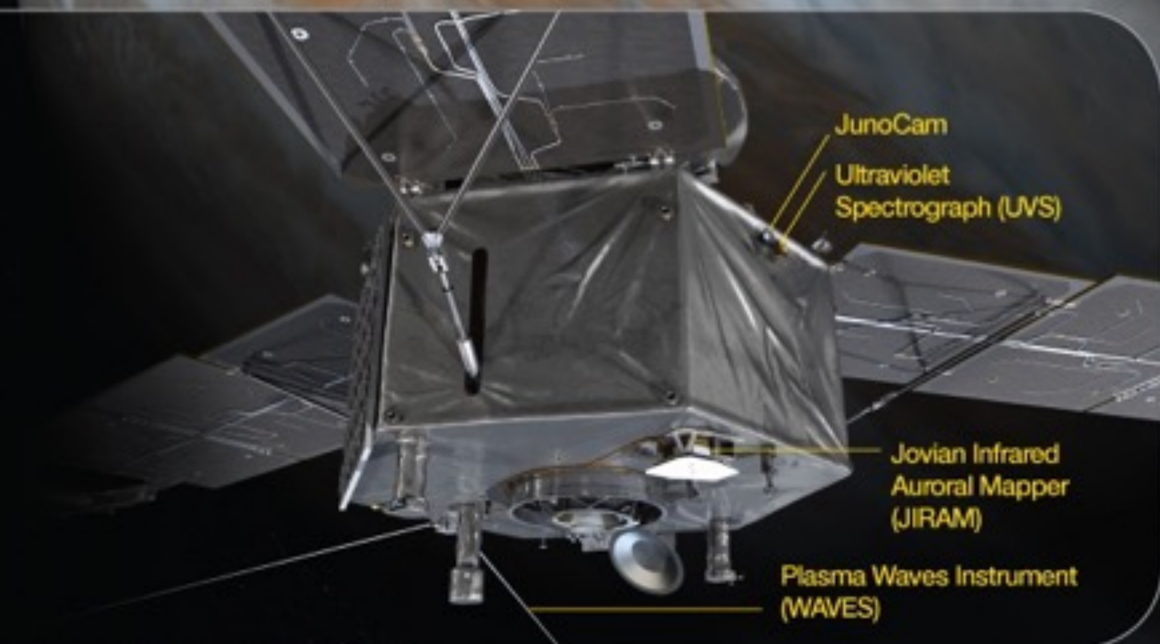
- Principal Investigator: Scott Bolton at Southwest Research Institute, USA.

Unlocking Jupiter's Secrets

- Origins: Determining how much water is in Jupiter's atmosphere
- Interior: Mapping Jupiter's magnetic and gravity fields
- Atmosphere: Looking deep into Jupiter's atmosphere
- Magnetosphere: Exploring and studying Jovian magnetosphere near the poles, especially auroras

National Aeronautics and
Space Administration

Juno Spacecraft



SPACECRAFT DIMENSIONS

Diameter: 66 feet (20 meters)
Height: 15 feet (4.5 meters)

For more information:
missionjuno.swri.edu &
www.nasa.gov/juno

Juno's Instruments

Gravity Science and Magnetometers
: Study Jupiter's deep structure by mapping the planet's gravity field and magnetic field

Microwave Radiometer
: Probe Jupiter's deep atmosphere and measure how much water (and hence oxygen) is there

JEDI, JADE and Waves
: Sample electric fields, plasma waves and particles around Jupiter to determine how the magnetic field is connected to the atmosphere, and especially the auroras (northern and southern lights)

UVS and JIRAM
: Using ultraviolet and infrared cameras, take images of the atmosphere and auroras, including chemical fingerprints of the gases present

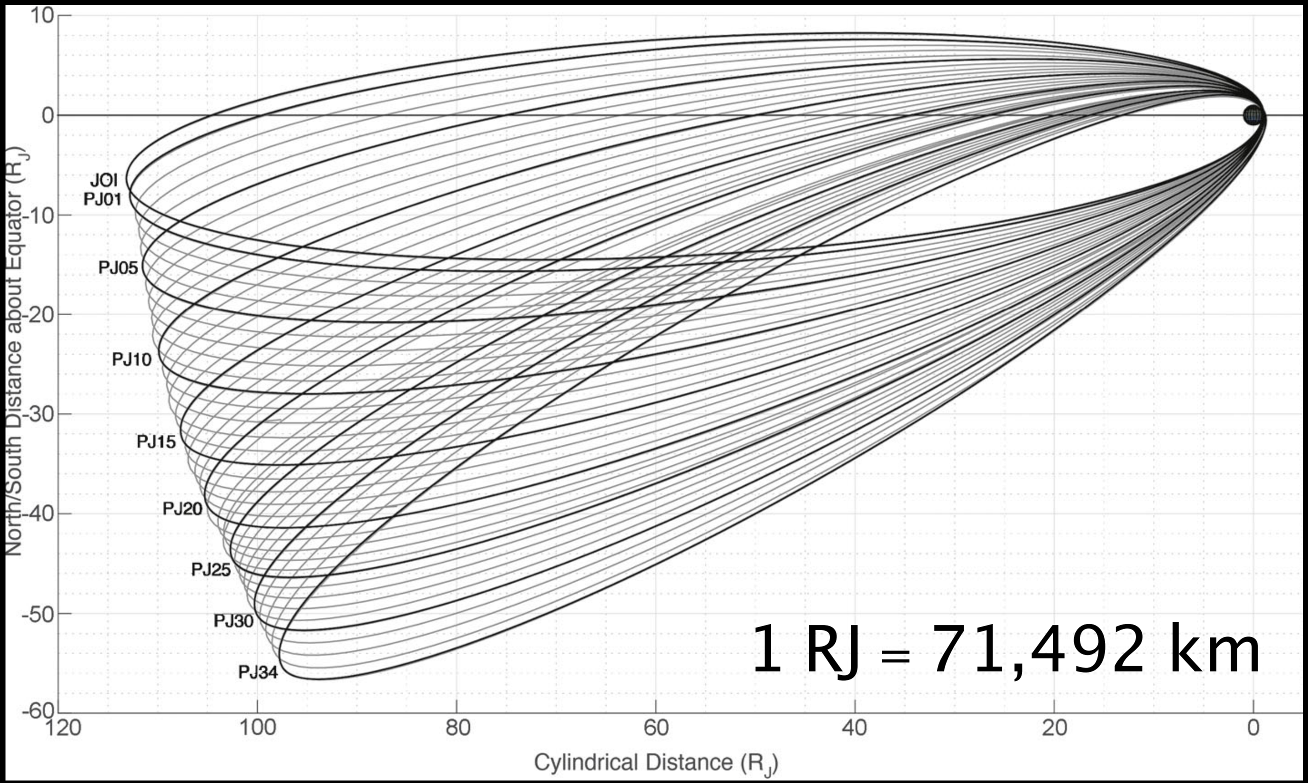
JunoCam
: Take spectacular close-up, color images

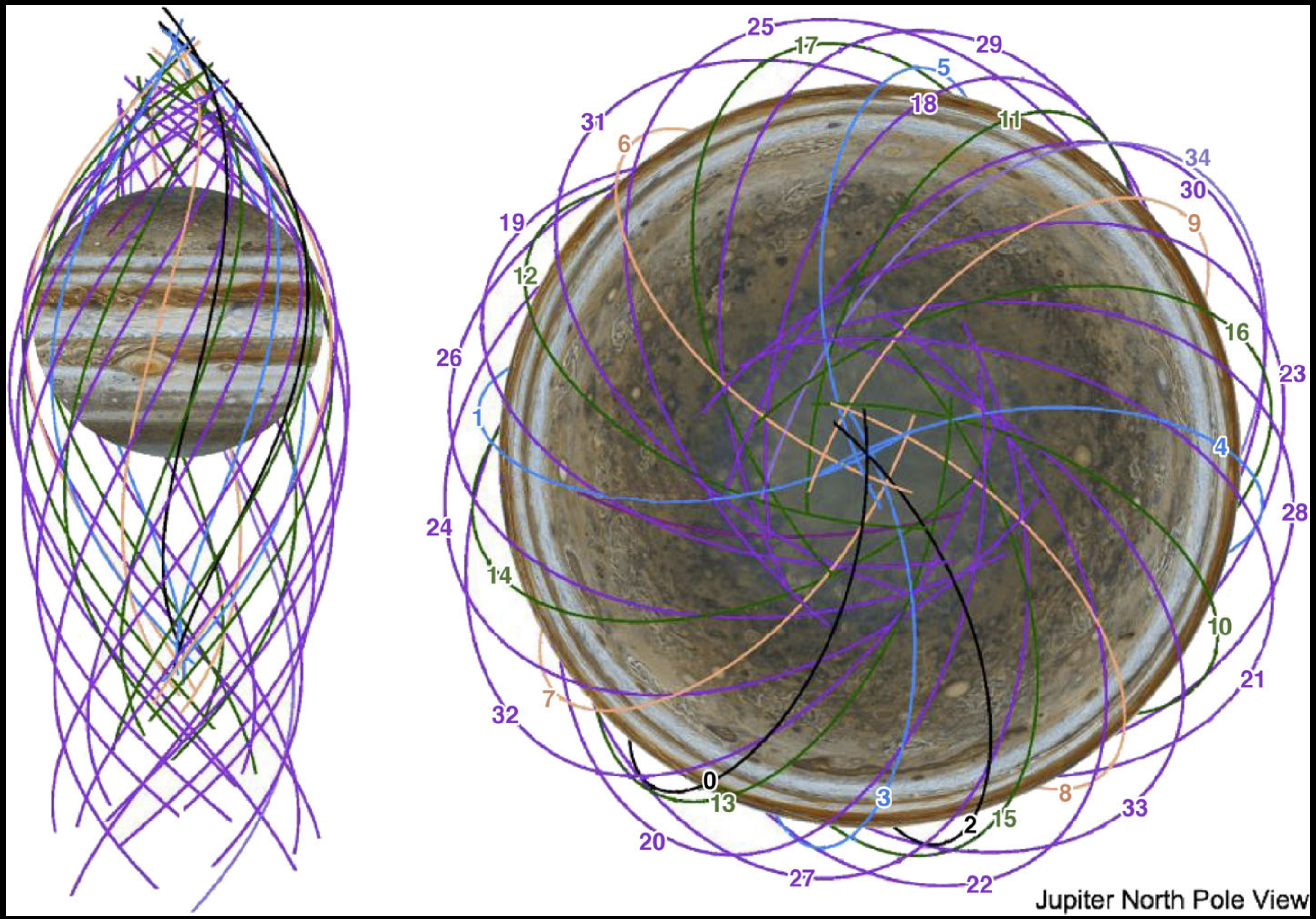
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

Juno orbital trajectory



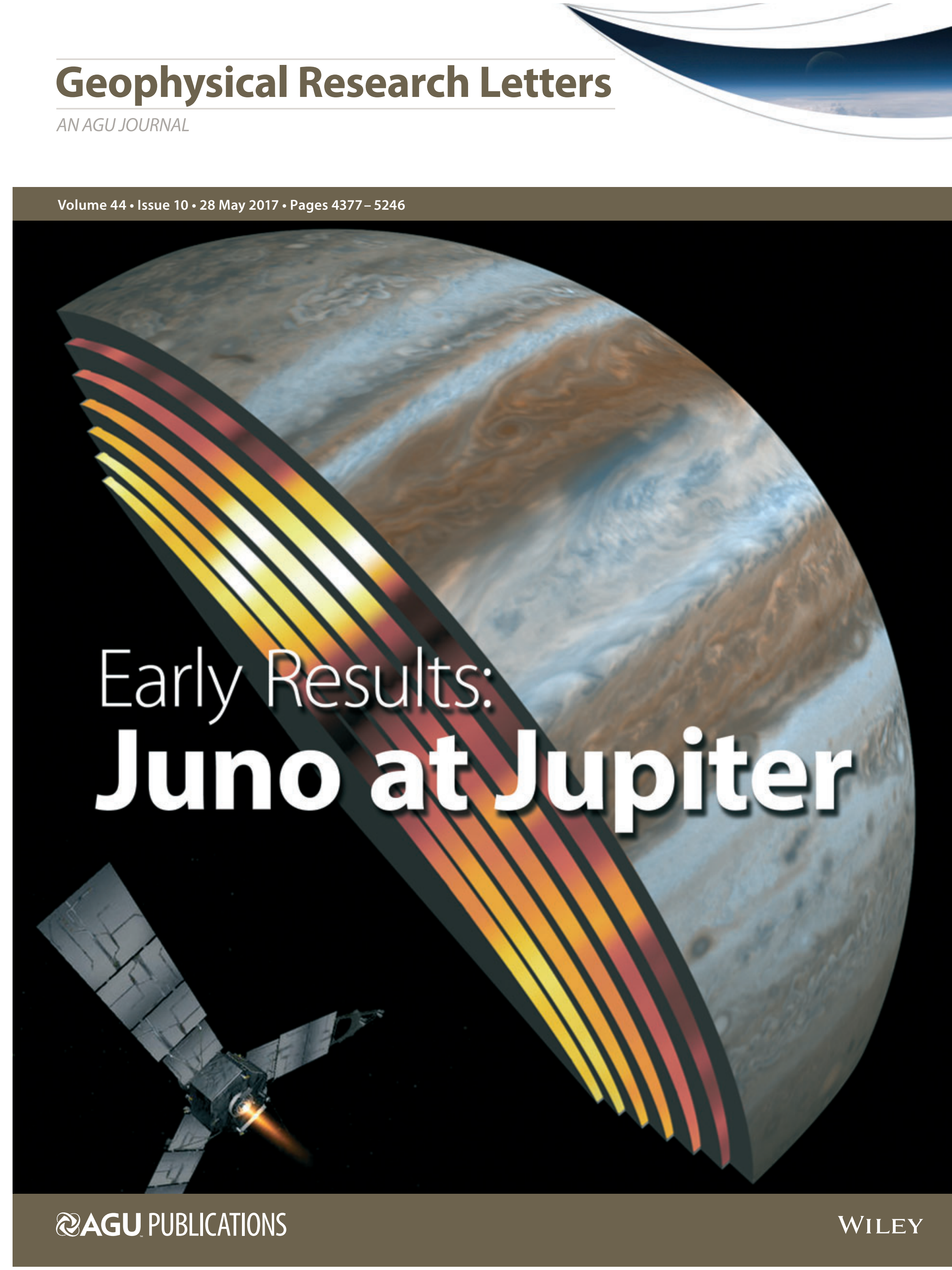


[Bolton+, SSR, 2017]

- JOI (PJ0): 07/05/2016 02:47
- PJ01: 08/27/2016 12:51
- PJ02: 10/19/2016 18:10
- PJ03: 12/11/2016 17:03
- PJ04: 02/02/2017 12:57
- PJ05: 03/27/2017 08:52
- PJ06: 05/19/2017 06:00
- PJ07: 07/11/2017 01:55
- PJ08: 09/01/2017 21:49
- PJ09: 10/24/2017 17:43
- PJ10: 12/16/2017 17:58 (Tomorrow!)
- PJ11: 02/07/2018 13:52

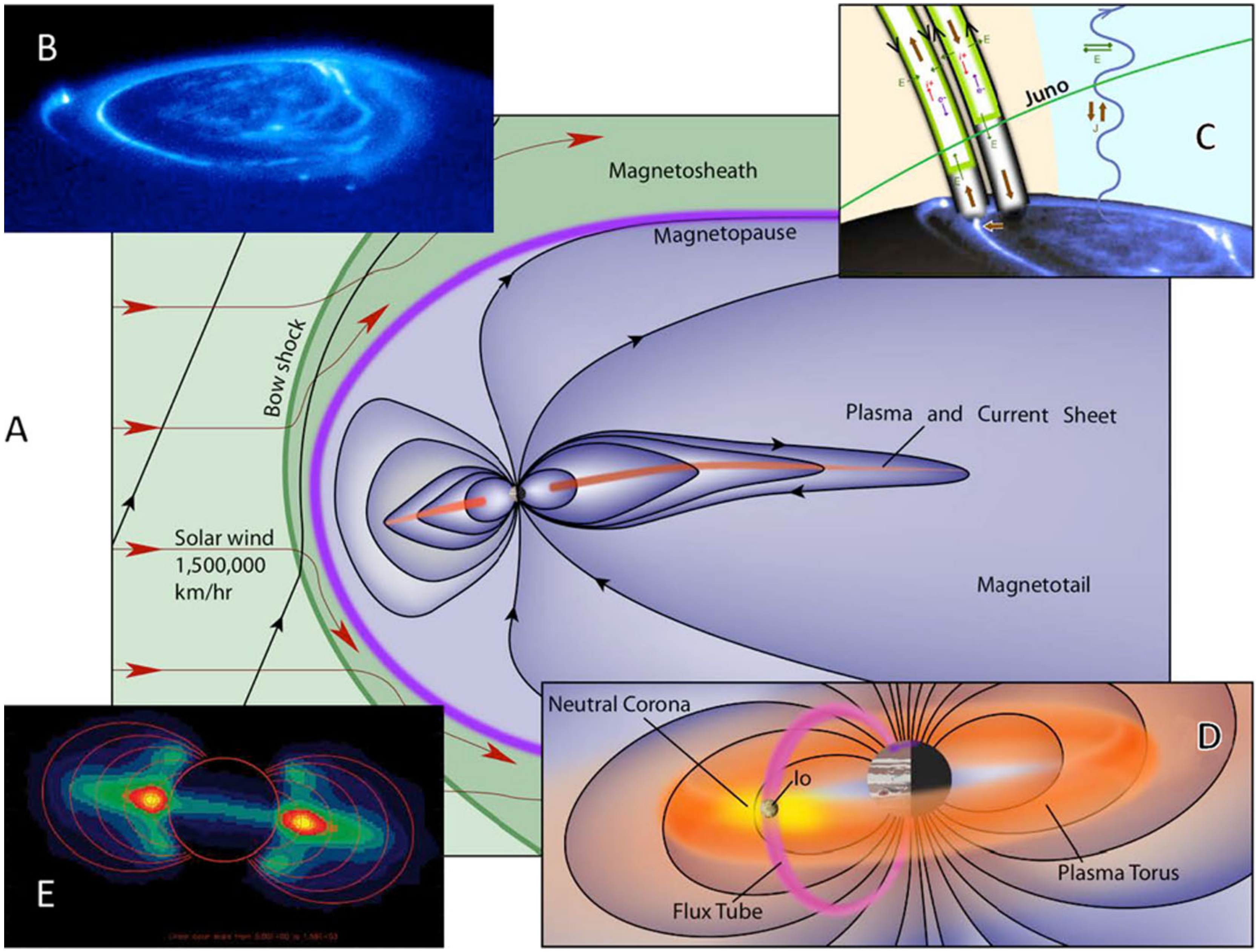
Juno's early results in May 2017

2 Overview Papers
(Bolton+ for Jovian interior deep atmosphere;
Connerney+ for Jovian magnetosphere)



50 Detailed Papers
(where three papers led by
Imai were collected)

Jovian magnetosphere science from Juno



A: Jupiter's magnetosphere (100 times larger than the Earth's one)

B: Jovian aurora in north pole taken by Hubble Space Telescope

C: Field-align currents at pole

D: Volcanic satellite Io producing plasma torus

E: Jovian radiation belt (MeV electrons) in synchrotron emission

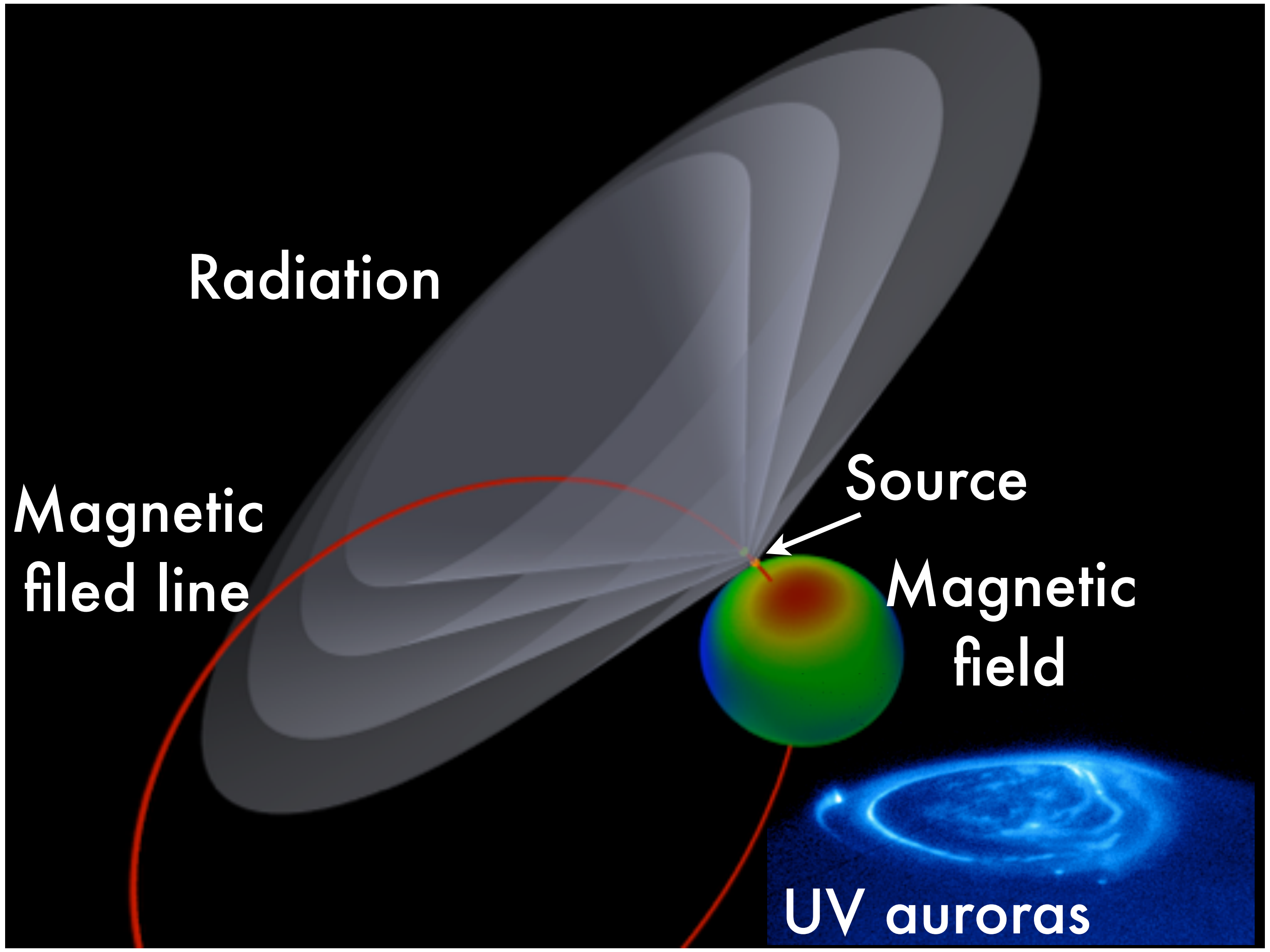
[Bagenal+, SSR, 2014]

Outstanding issues to be addressed by Juno

- What is the high latitude structure of the magnetosphere?
- Where and how are the particles that excite the aurora accelerated?
- Where and how is auroral radio emission generated?
- What mechanisms accelerate particles to radiation belt energies?

[After Bagenal+, SSR, 2014]

Jupiter's auroral radio emissions



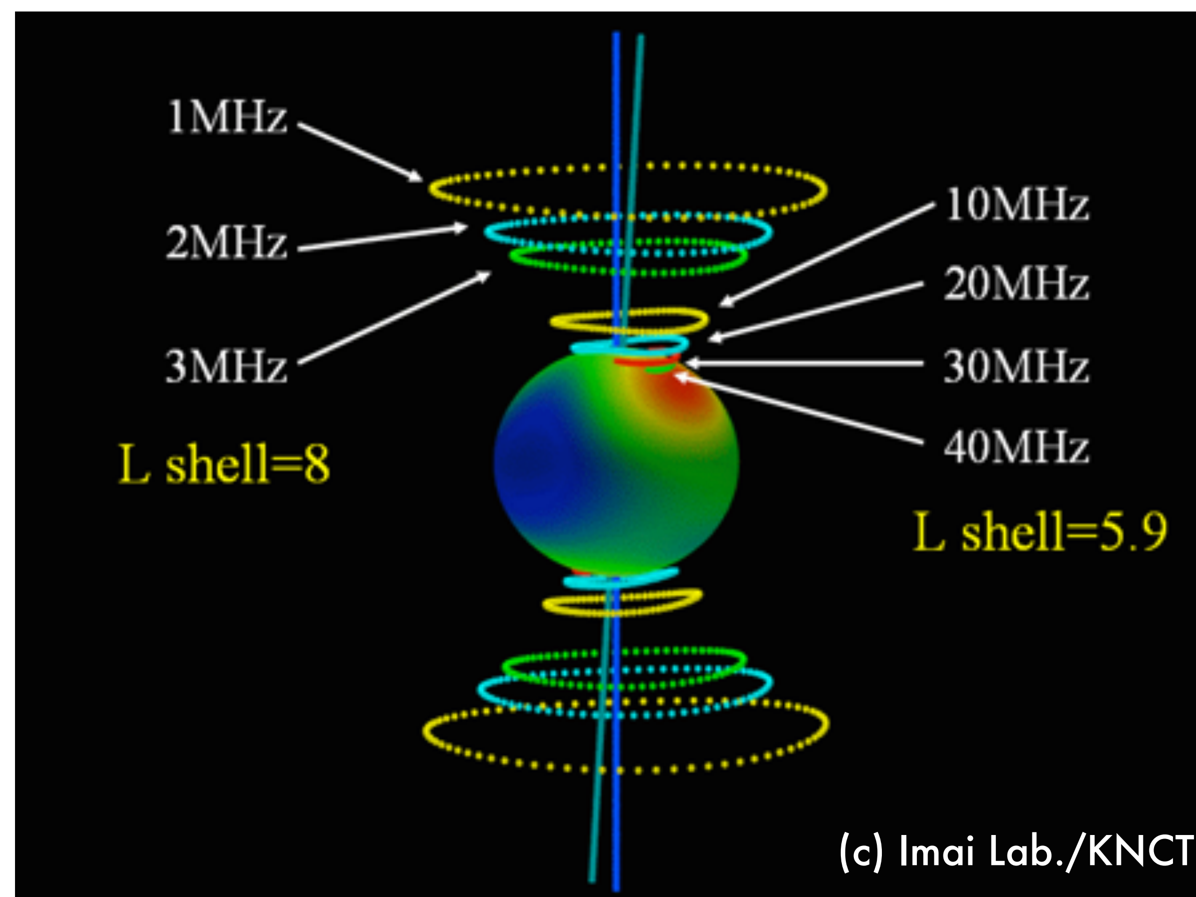
(c) NASA/Clarke

Jupiter's auroral radio emissions have such properties as:

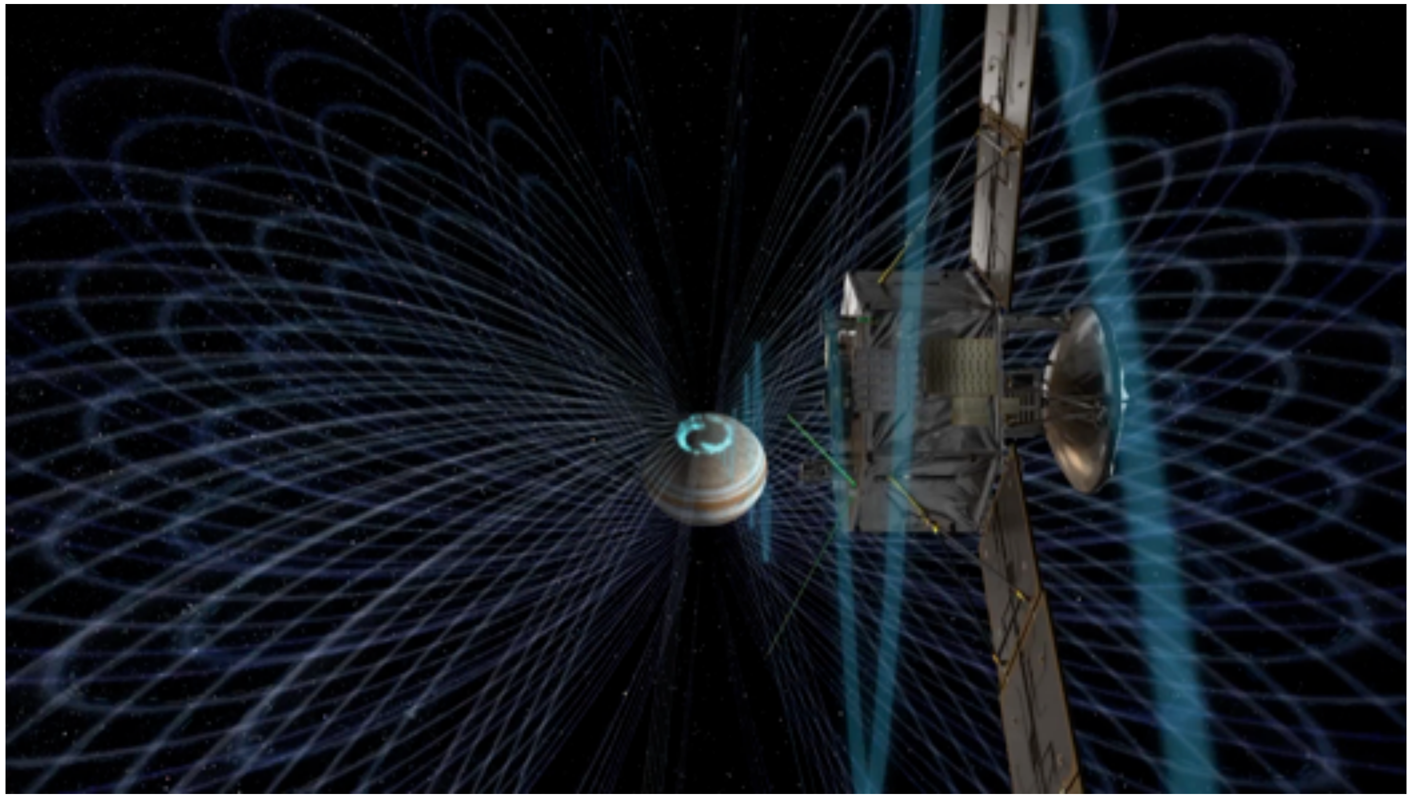
1. Non-thermal, strong bursts
2. Highly elliptically/circularly polarization
3. Emission frequency close to electron gyrofrequency via electron cyclotron maser instability
4. Anisotropic emission beam from a radio source along a magnetic field line

Frequency	Term
1 - 40 MHz	Decameter (DAM)
0.3 - 10 MHz	Hectometer (HOM)
10 k - 1 MHz	Kilometer (bKOM)

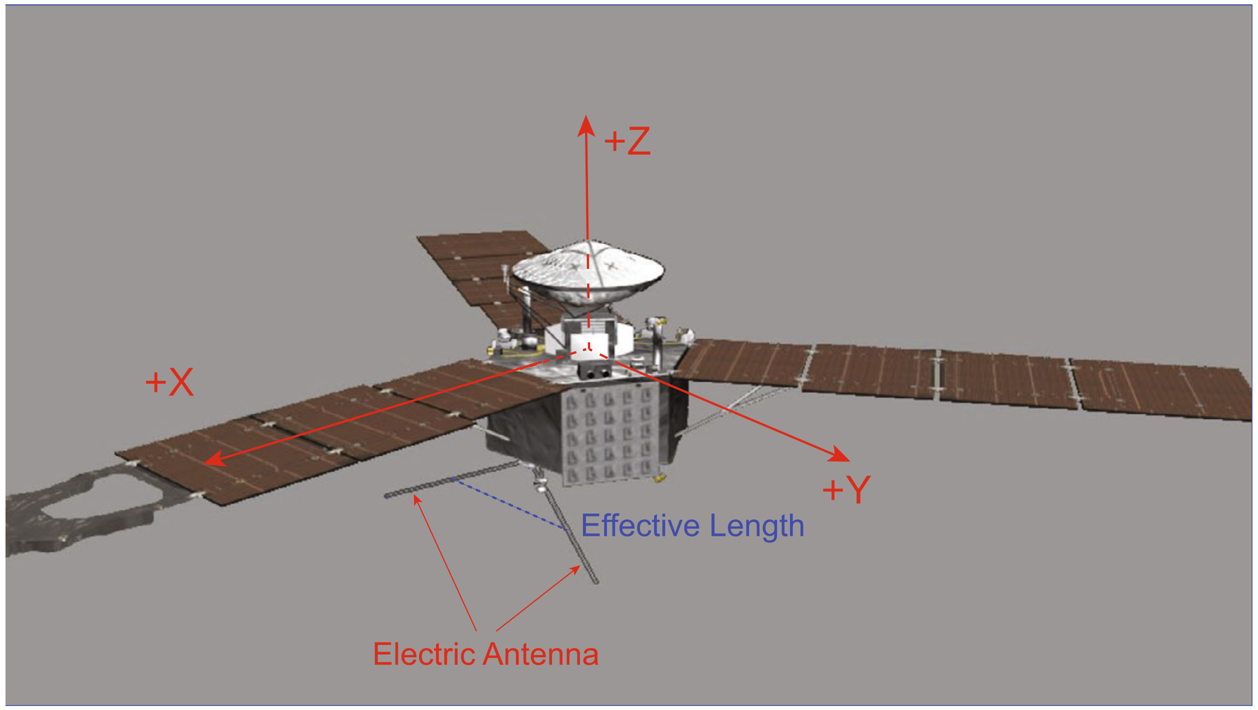
[cf. Carr+, 1983; Zarka, 1998; Clarke+, 2004; Imai+, 2011a]

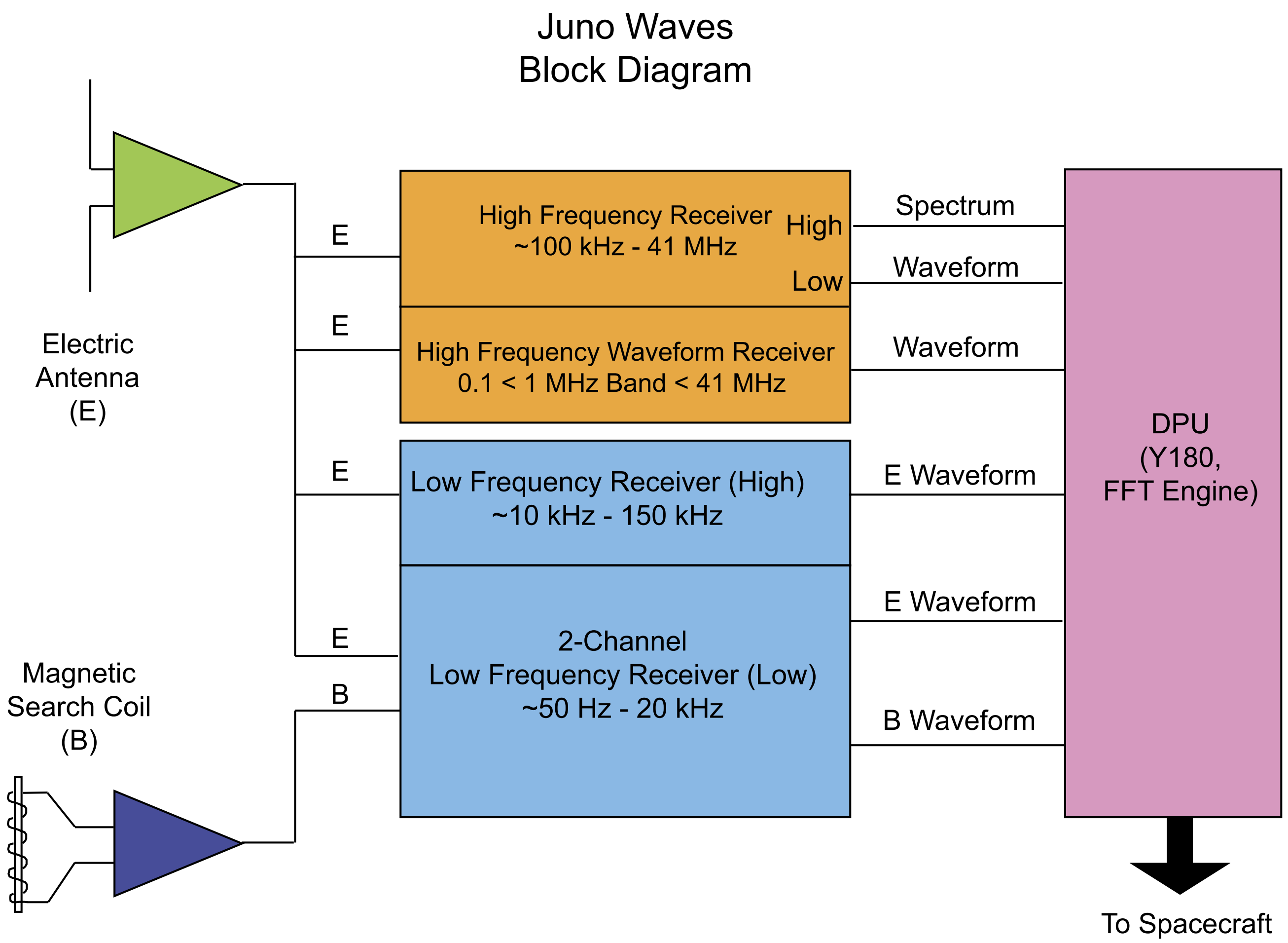


Juno Waves instrument



[NASA/JPL-Caltech]

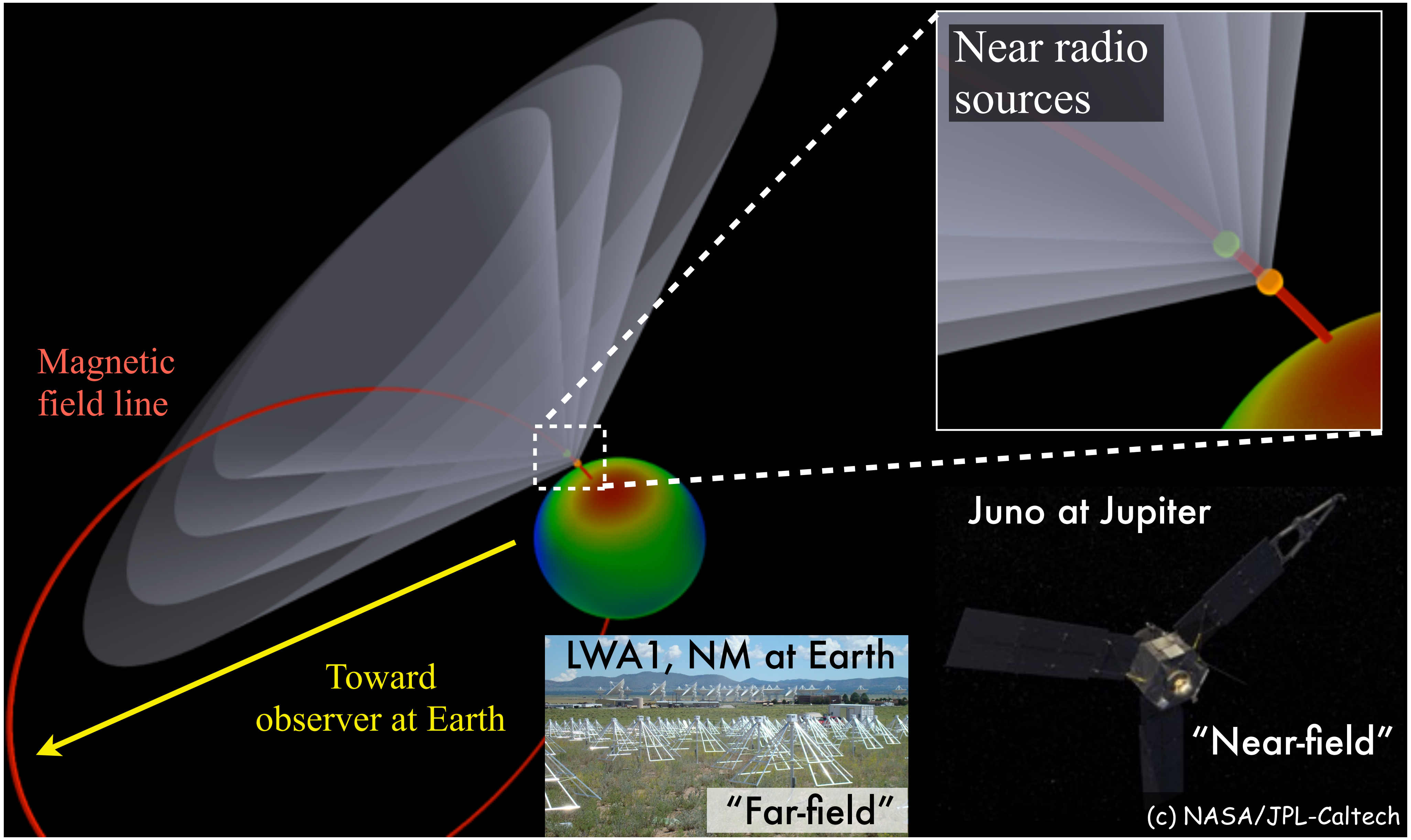




University of Iowa
radio and plasma wave (Waves) instrument
[Kurth+, SSR, 2017]

E-field	50 Hz-40 MHz from electric dipole antenna
B-field	50 Hz-20 kHz from magnetic search coil sensor
Receivers	1 x LFR, 2 x HFR
Frequency bands	five different bands

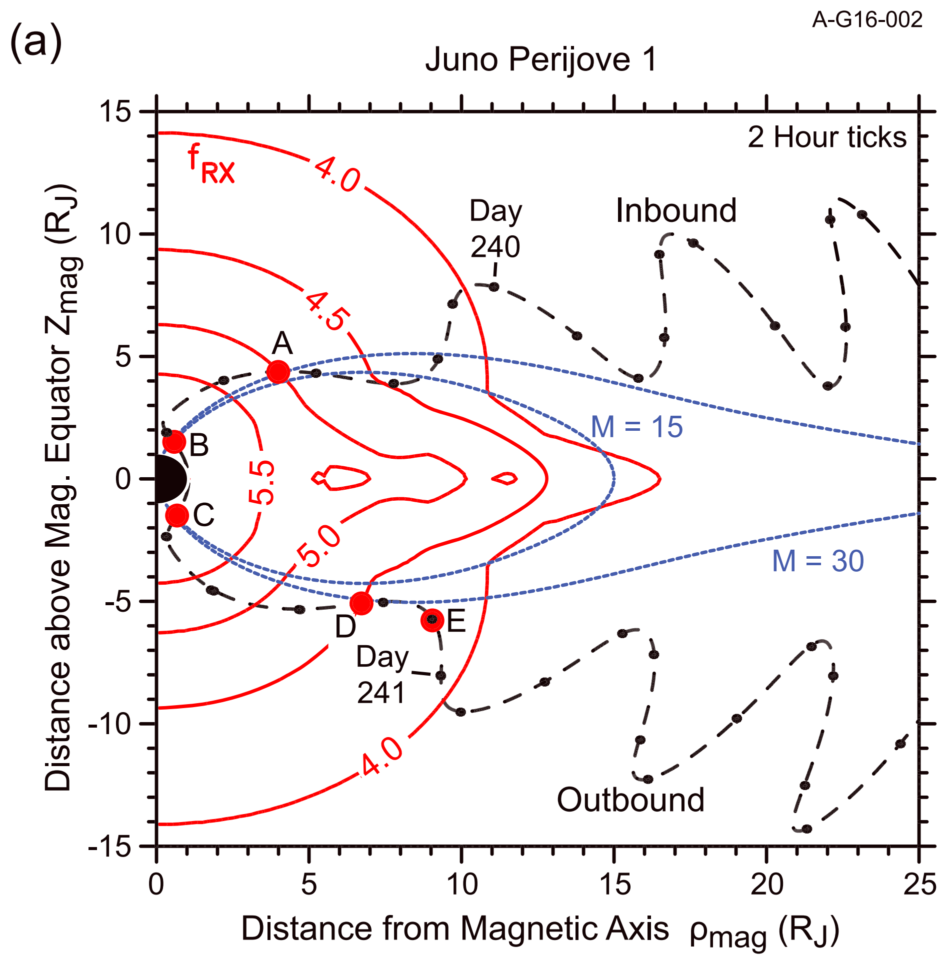
Juno's advantages for Jovian radio emissions

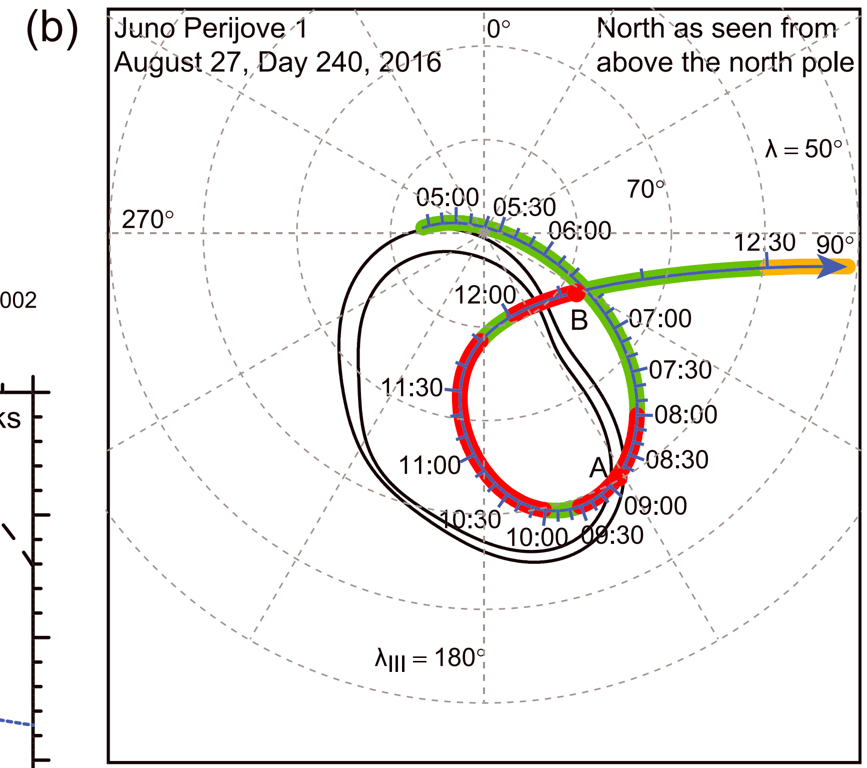


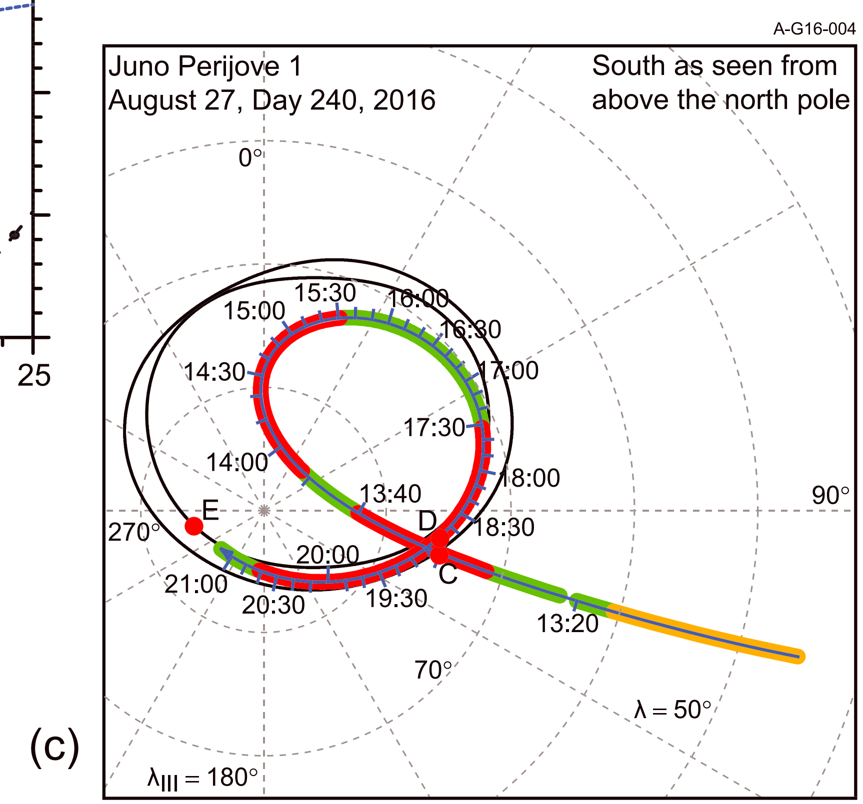
Juno can determine the radio source locations and the beaming properties, by

1. identifying emission frequency close to the local gyrofrequency with in situ particle measurements through Juno's perijove surveys [Kurth+, GRL; Louarn+, GRL],
2. computing wave k vectors from spin-modulated spectral density [Imai+, GRL, c],
3. performing stereoscopic radio observations with Juno and an Earth-based radio telescope [Imai+, GRL, a; Louis+, GRL] or investigating statistical characteristics of Jovian radio occurrence [Imai+, GRL, b] with the aid of Jovian radio beaming model.

1. Juno in-situ surveys



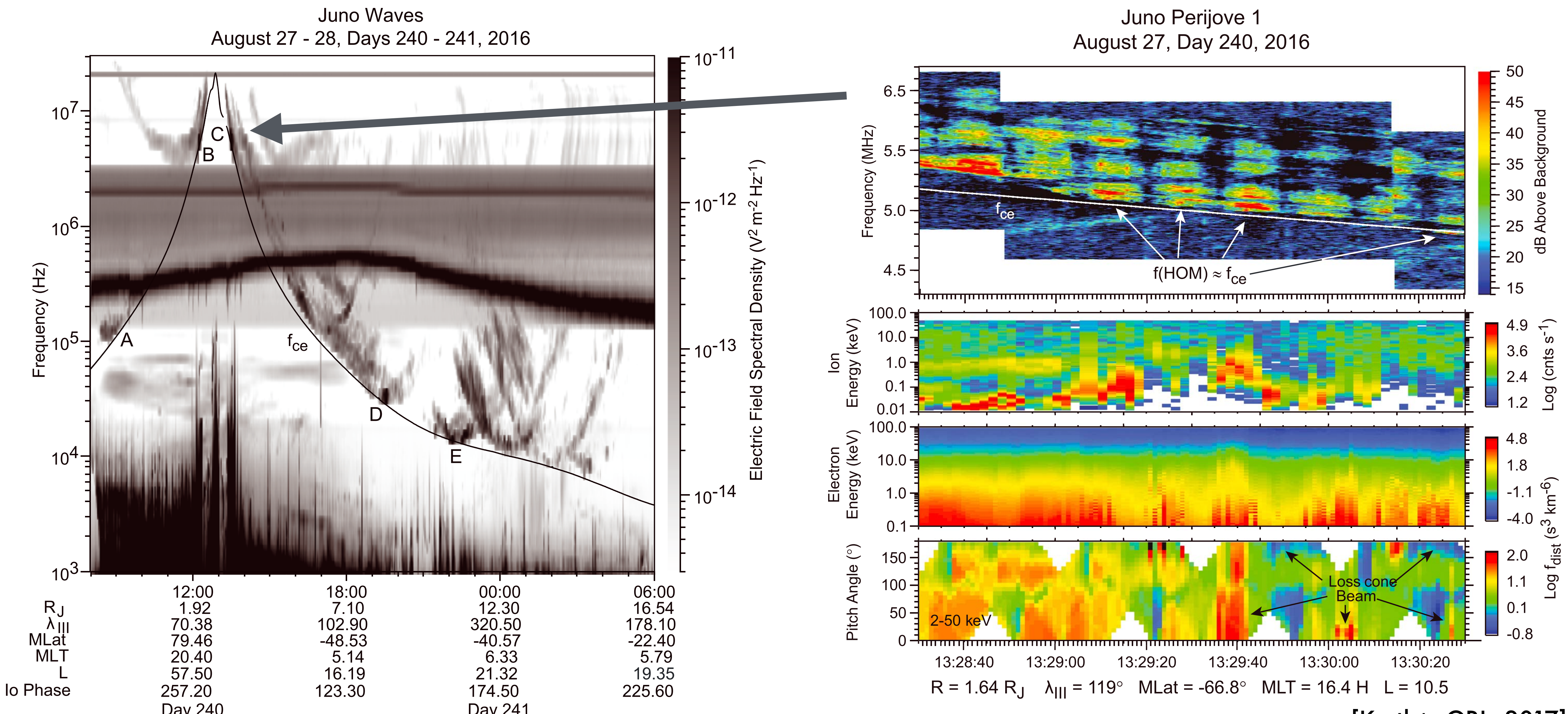




1 RJ = 71,492 km

[Kurth+, GRL, 2017]

1. Juno in-situ surveys

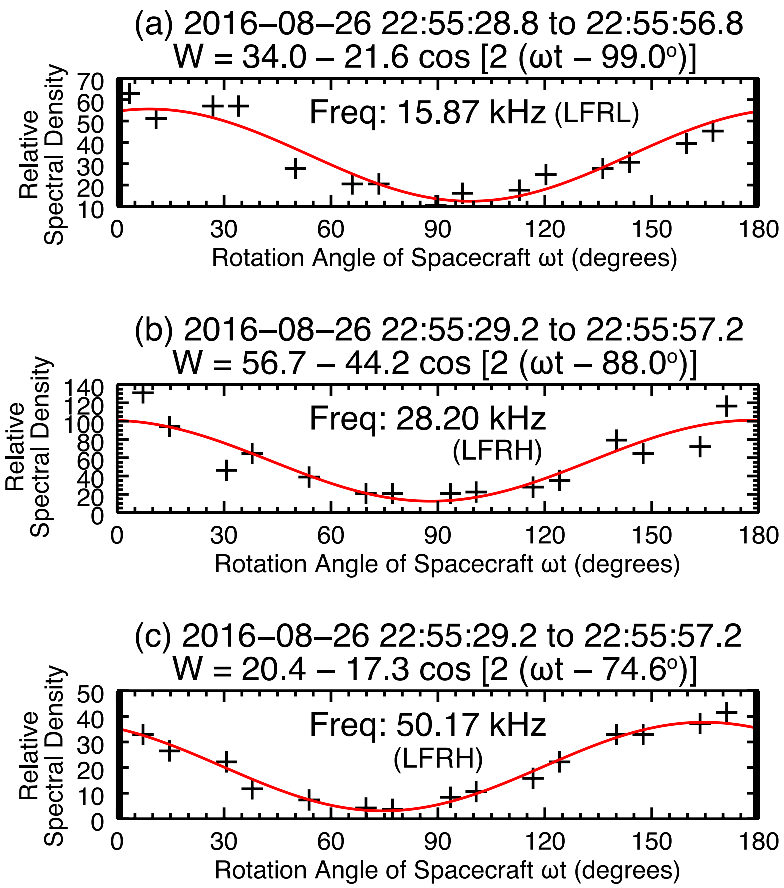


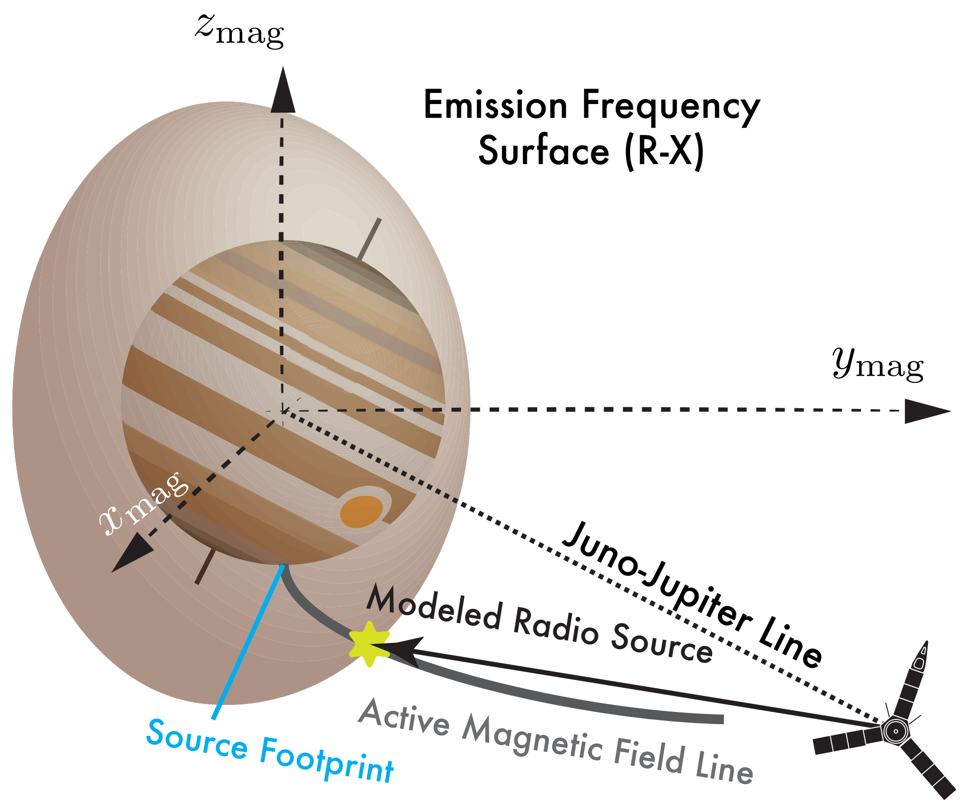
[Kurth+, GRL, 2017]

- Juno can identify emission frequencies close to the local electron cyclotron frequency at the auroral radio source during Juno's perijove surveys from pole to pole.

- The HOM emissions in Event C where accounted by the loss cone-driven CMI theory, in which up-going electron populations were at 5-10 keV and the amplified HOM waves propagated at 82°-87° from the B field vector [Louarn+, GRL, 2017].

2. Juno direction-finding analysis





[Adapted from Imai+, GRL, 2017c]

- Examples of least-square fits of the observed spectral density versus rotation angle of Juno for observed frequency.

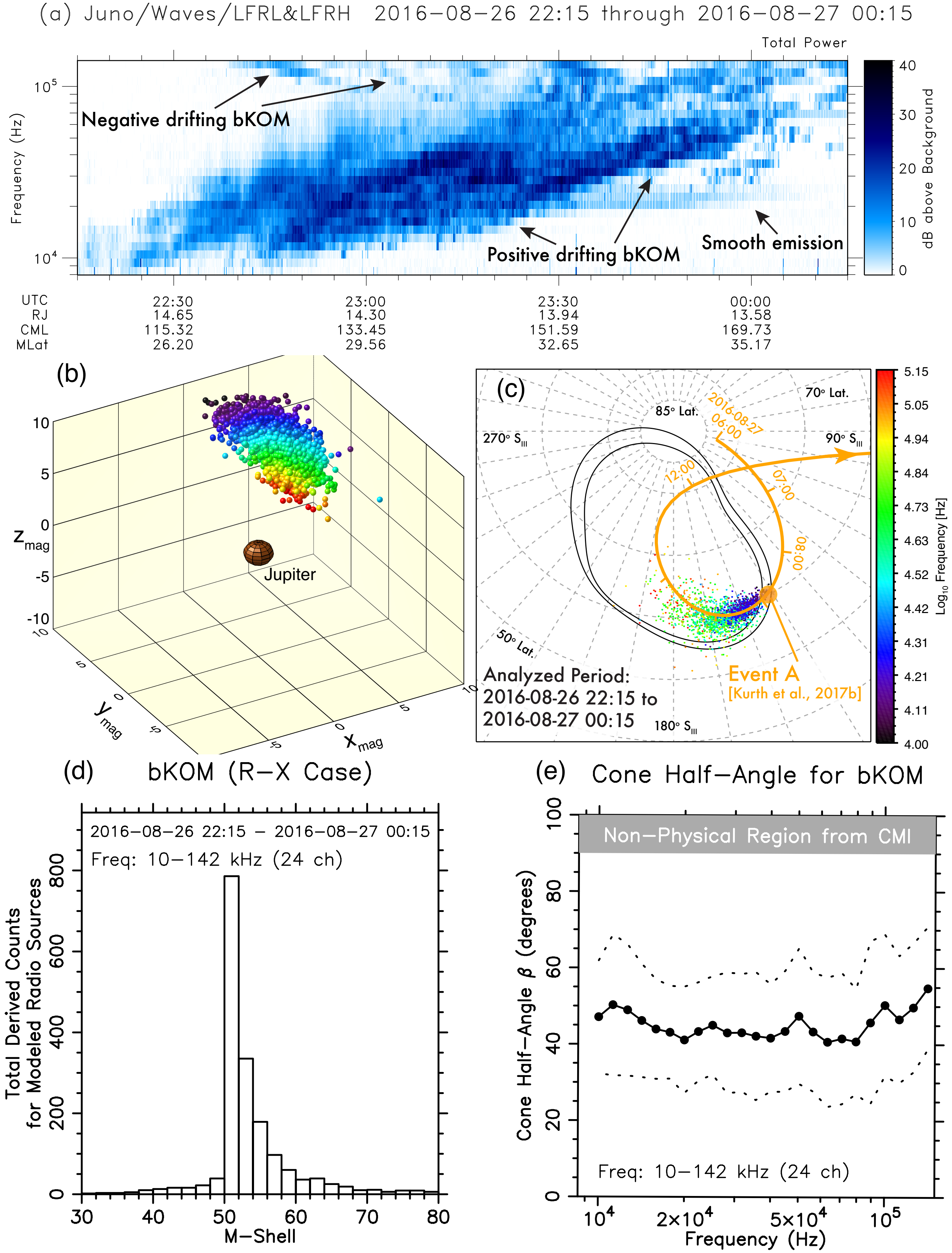
- The modulated intensity may be expressed [Lecacheux, 1978] as

$$W = W_0 \left[\left(1 - \frac{m^2}{2} \right) - \frac{m^2}{2} \cos \left[2 \left(\omega t - \phi_{\mathrm{SC}} \right) \right] \right],$$

where modulation index m is $\sin \theta_{sc}$.

- The modeled radio source is located on the emission frequency surface (based on the existing Jovian magnetic field and plasma models) and intersects the k vectors derived from the direction-finding method.

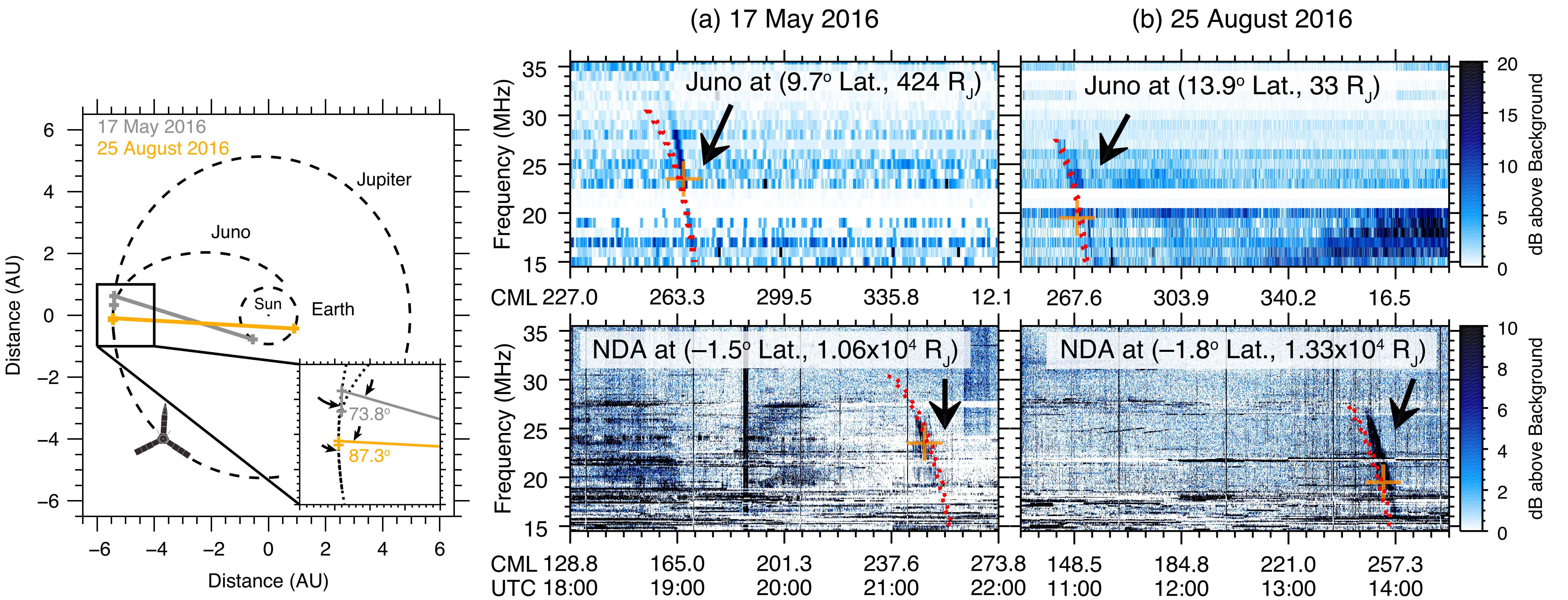
2. Initial DF results of bKOM from Juno Perijove 1



[Adapted from Imai+, GRL, 2017c; PRE8, 2017d]

- Our bKOM radio footprints are close to the inner edge of the empirical mail oval, in good agreement with the Juno footprints during the near-source crossing [Kurth+, GRL, 2017b; PRE8, 2017c].
- The M-shell (similar to L-shell but with a non-dipole field model) of these radio sources ranges from 50 to 60, compared to M-shell=5-58 [Ladreiter+, PSS, 1994]
- The mean cone half-angle extends from 40° to 55°, consistent with that of 30° to 80° based on the Ulysses DF study [Ladreiter+, PSS, 1994]

3. Stereoscopic radio observations with Juno

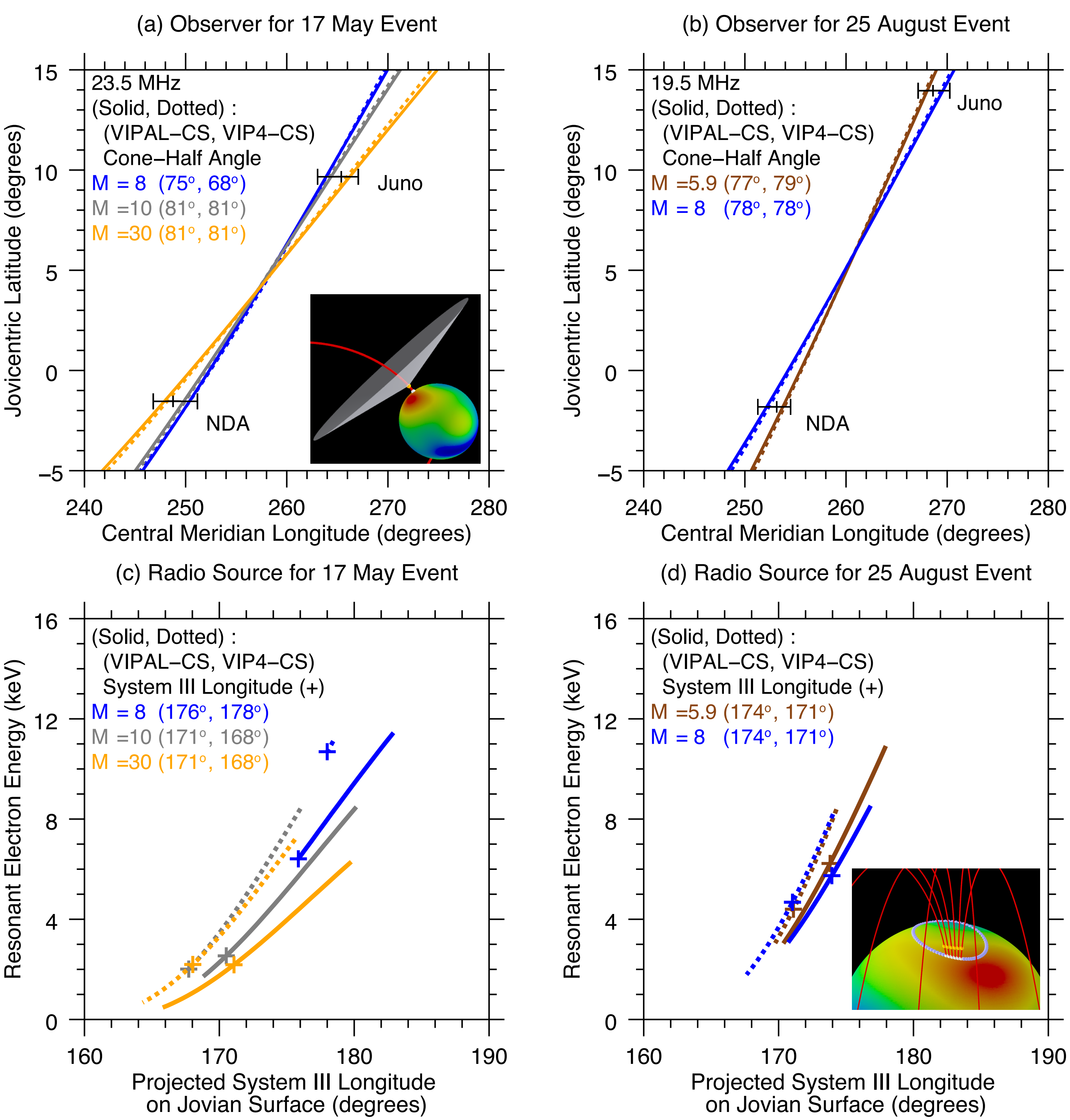


[Imai+, GRL, 2017a]

- Two well-defined Jovian DAM radio arcs were observed at latitudinal separations of 11°–16° from the Juno spacecraft near Jupiter and the Nançay Decameter Array (NDA) at Earth on 17 May and 25 August, 2016.

- By means of measurements of the wave arrival time at two distant observers with propagation time correction, the remaining delay times are 92.8 ± 1.3 min for the first arc and 116.0 ± 1.2 min for the second arc.

3. Stereoscopic radio observations with Juno



[Imai+, GRL, 2017a]

- Modeling arcs as viewed from Juno and NDA at different latitudes and from radio sources mapped onto the Jovian atmosphere.

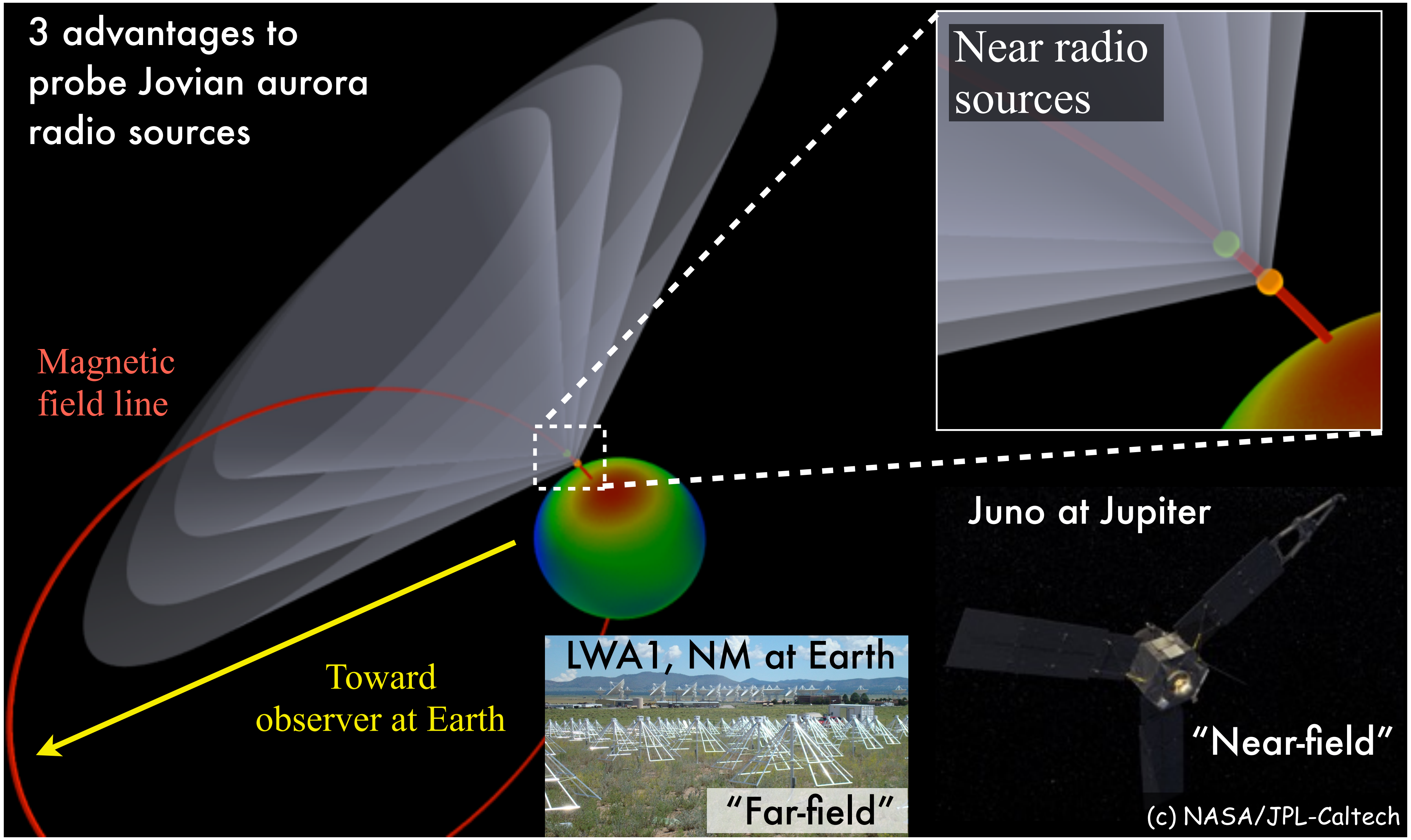
- According to the loss-cone driven CMI theory [Hess+, GRL, 2008],

$$\Theta\left(f\right) = \arccos\left[\left(v_e/c\right)/\sqrt{1 - f/f_{g,max}}\right],$$

where v_e is the velocity of the resonant electron.

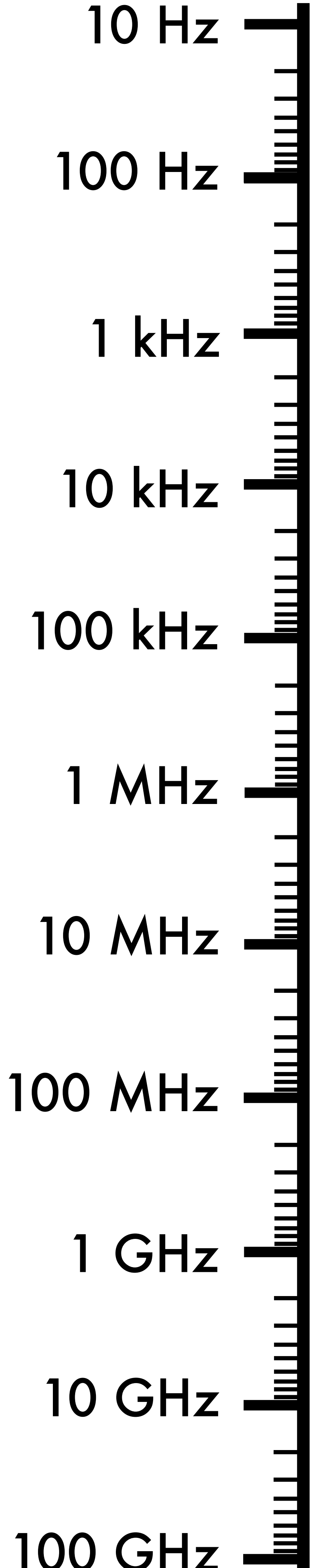
- The radio sources are estimated to be located at about 173° ± 10° in System III longitude projected onto the Jovian surface, implying resonant electron energy ranges from 0.5 to 11 keV in the source.

Summary

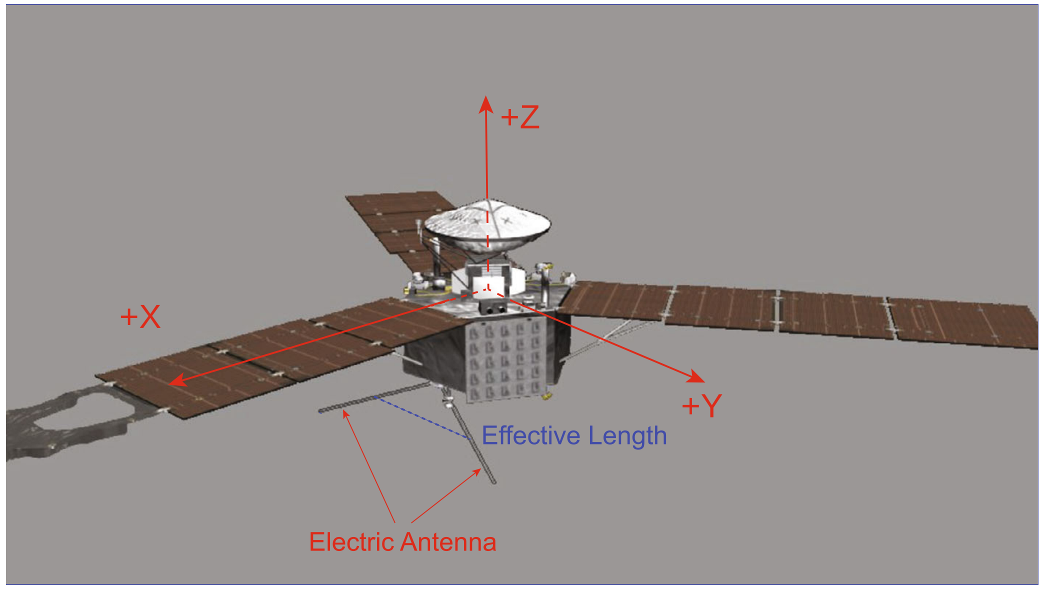


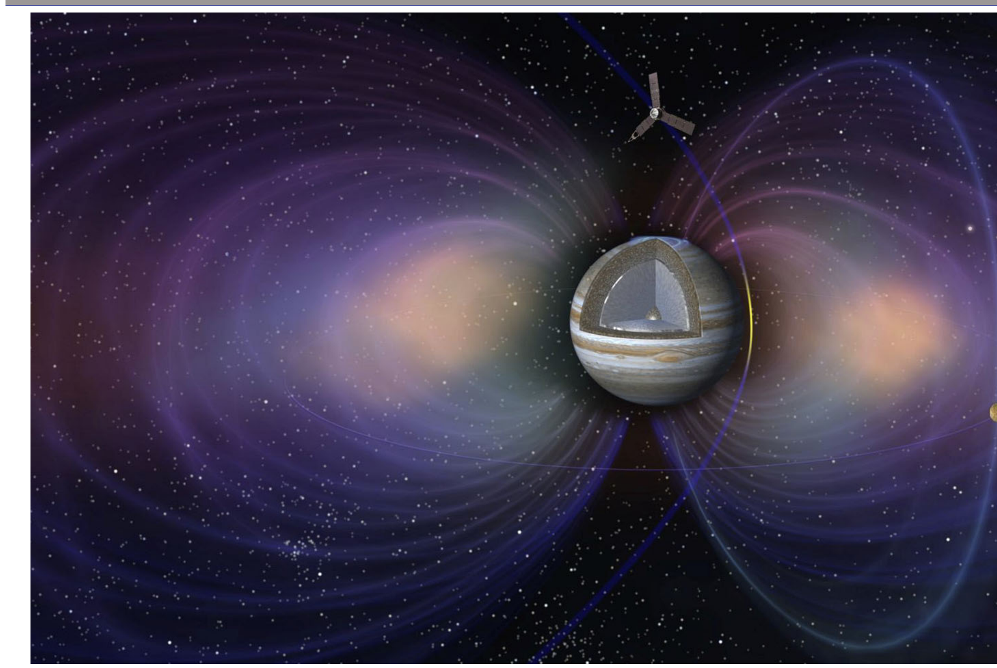
1. First advantage is to examine the detection of emissions compared to the local gyrofrquency as well as in situ particle measurements on board Juno. Juno's proximity to Jupiter is a prime advantage.
2. Estimating the direction-of-arrival of incoming waves from the spin-modulated spectral density is the second advantage.
3. With a Jovian radio beaming model, the third advantage is a comparison of stereoscopic radio observations from various vantage points.

Juno Radio Observations



Waves instrument [Kurth+, SSR, 2017]





[Bolton+, SSR, 2017]

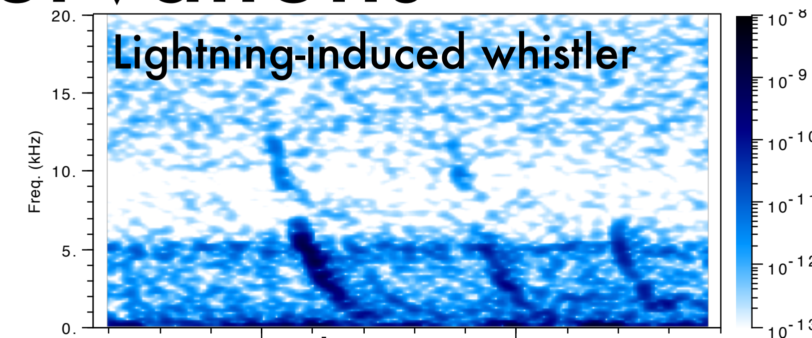
MWR instrument [Janssen+, SSR, 2017]

Waves

- Auroral radio emission & plasma waves
- Other waves (thermal plasma, dust, & lightning)

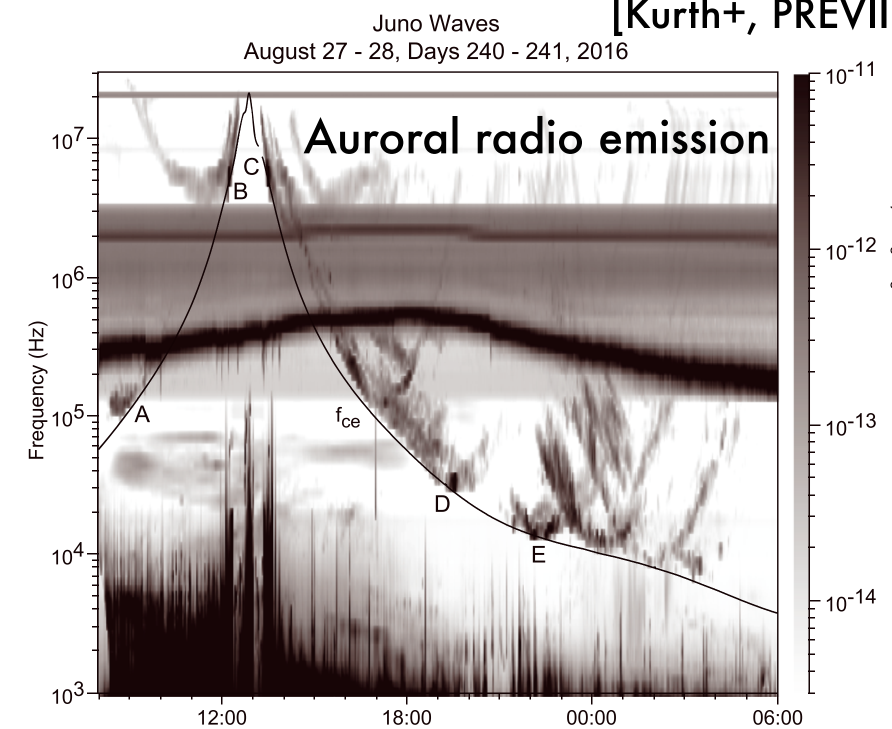
MWR

- Global water abundance
- Atmospheric dynamics
- Radiation belts

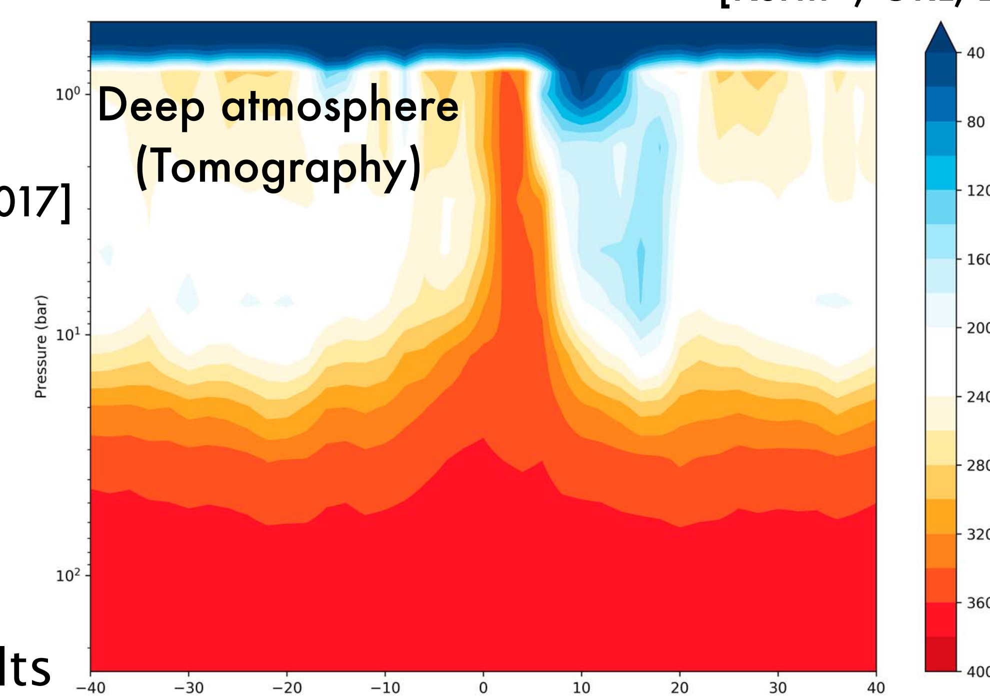


122-ms snapshot on August 27, 2016

[Kurth+, PREVIII, 2017]

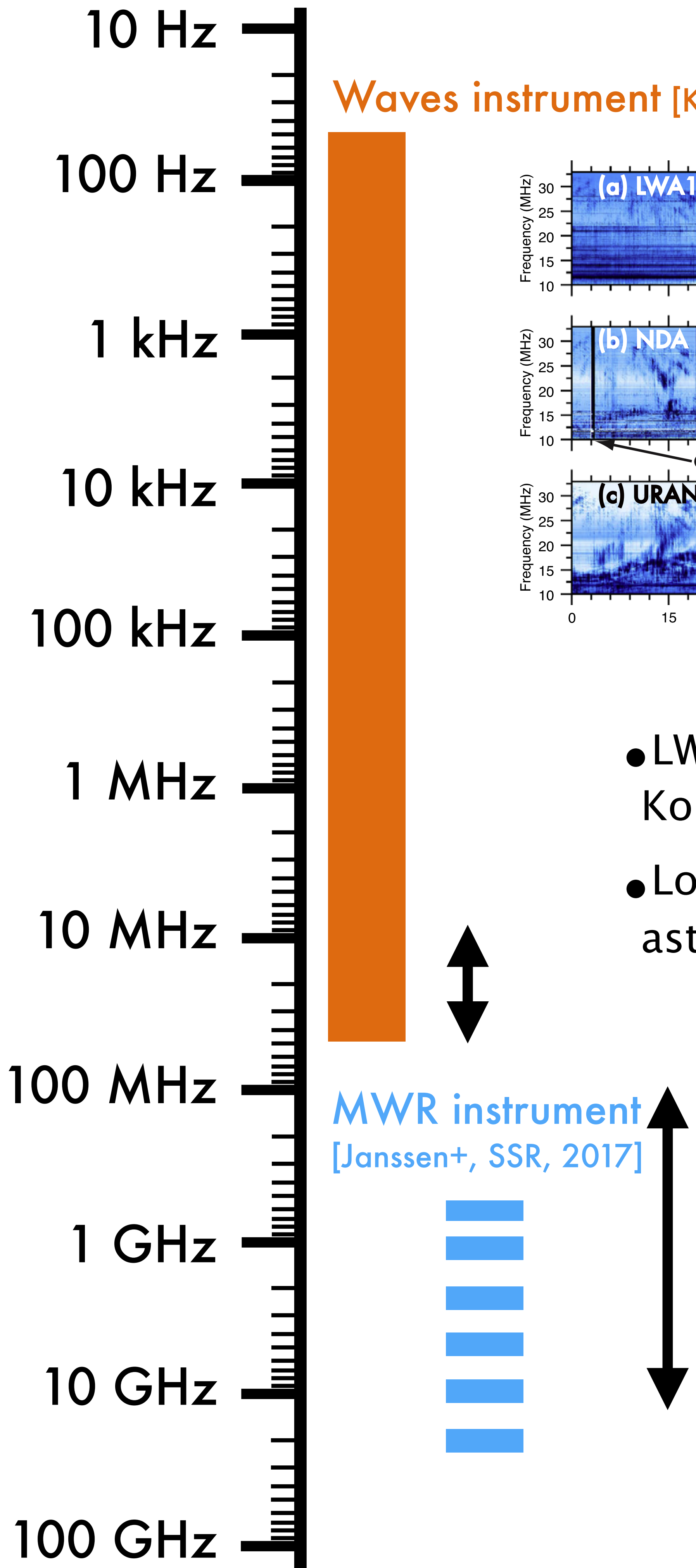


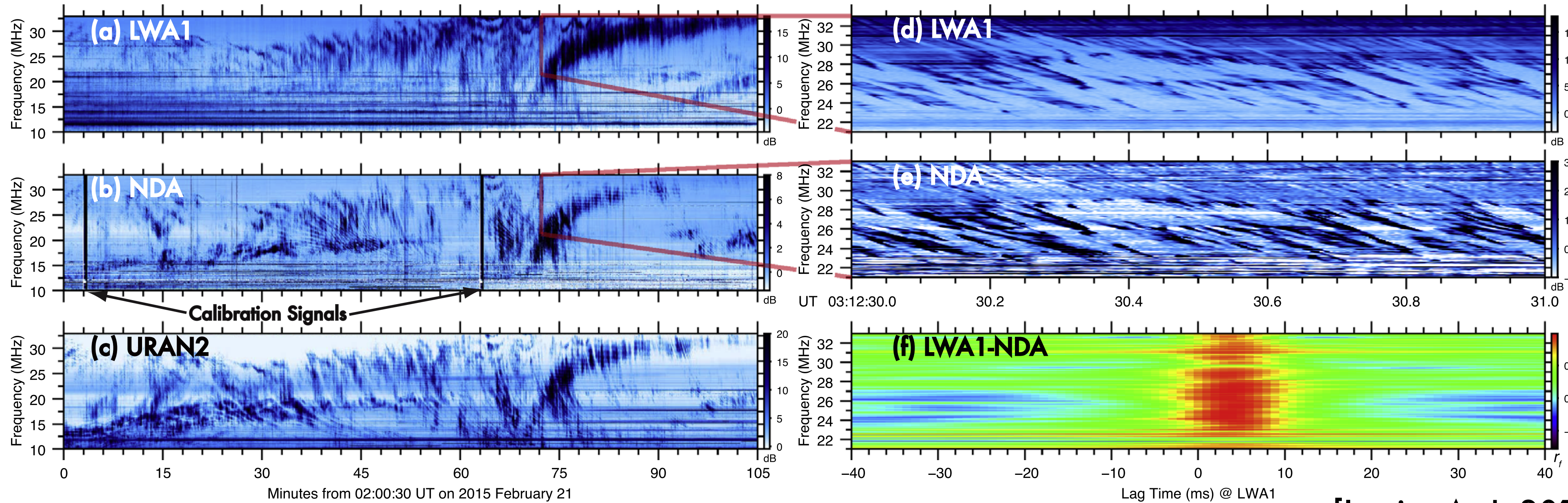
[Kurth+, GRL, 2017]



[Bolton+, Scirnce, 2017; Li+, GRL, 2017]

Earth-based Jovian radio observations in concert with Juno

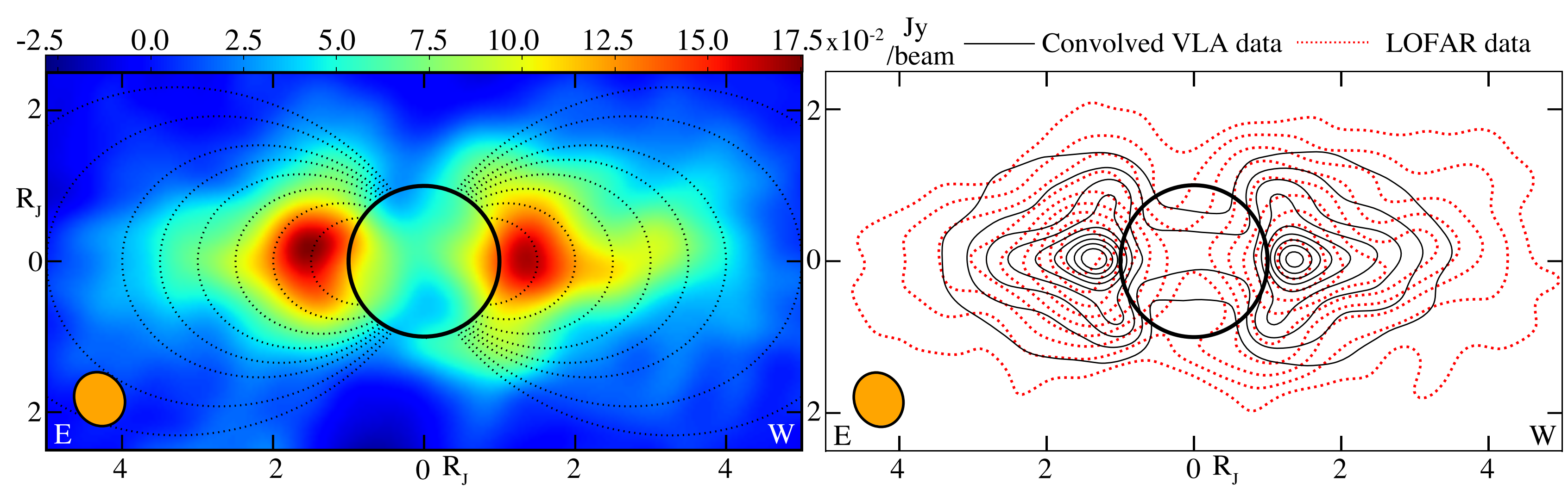




[Imai+, ApJ, 2016]

Jovian auroral radio emission

- LWA1 (PI: M. Imai), NDA (Dir: L. Lamy), UTR2, URAN1-4 (Dir: A.A. Konovalenko), & OVRO-LWA (PI: M. Anderson)
- Log-periodic antenna (5 Univ. in Japan) & amateur radio astronomers (NASA's RadioJove project)

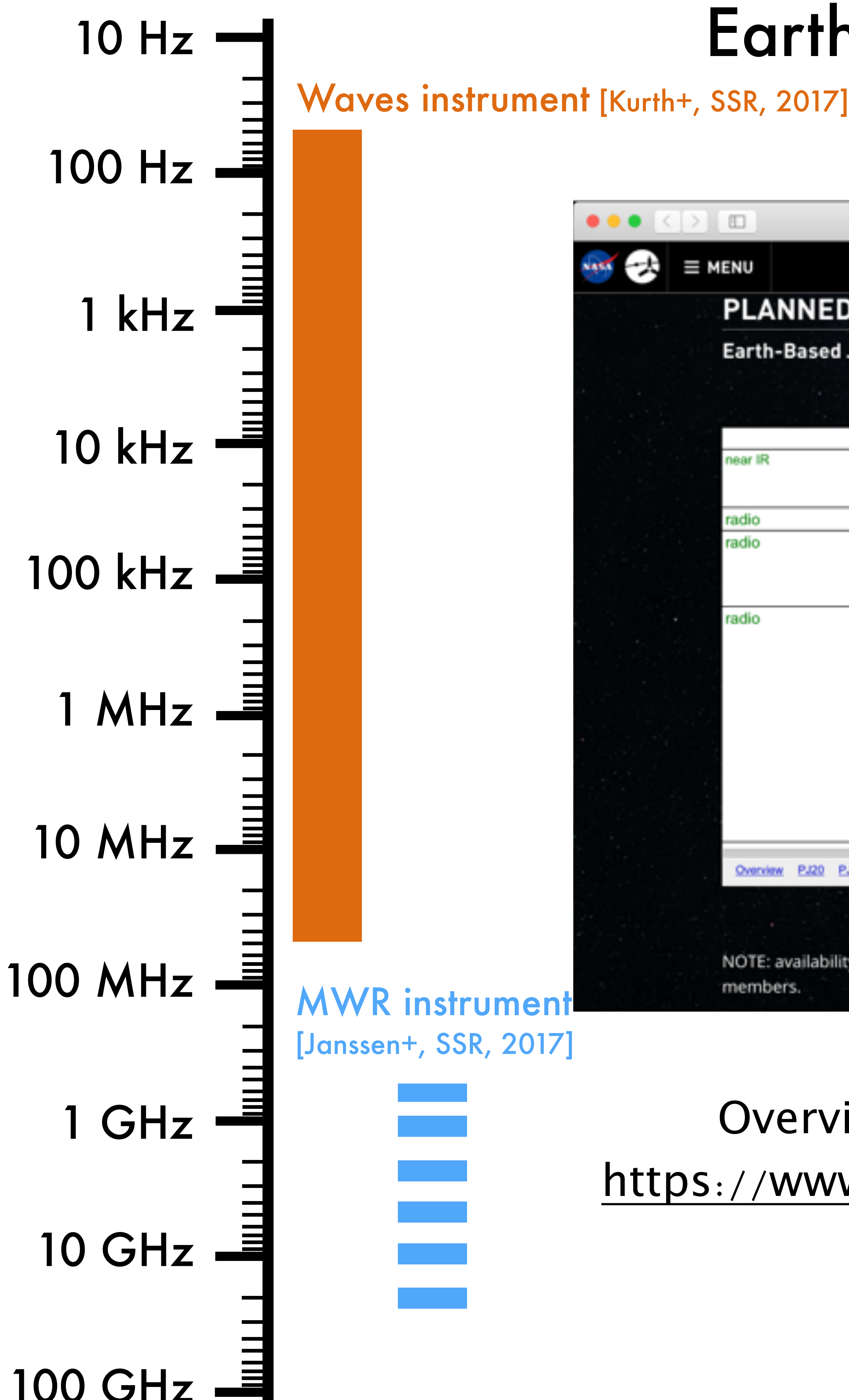


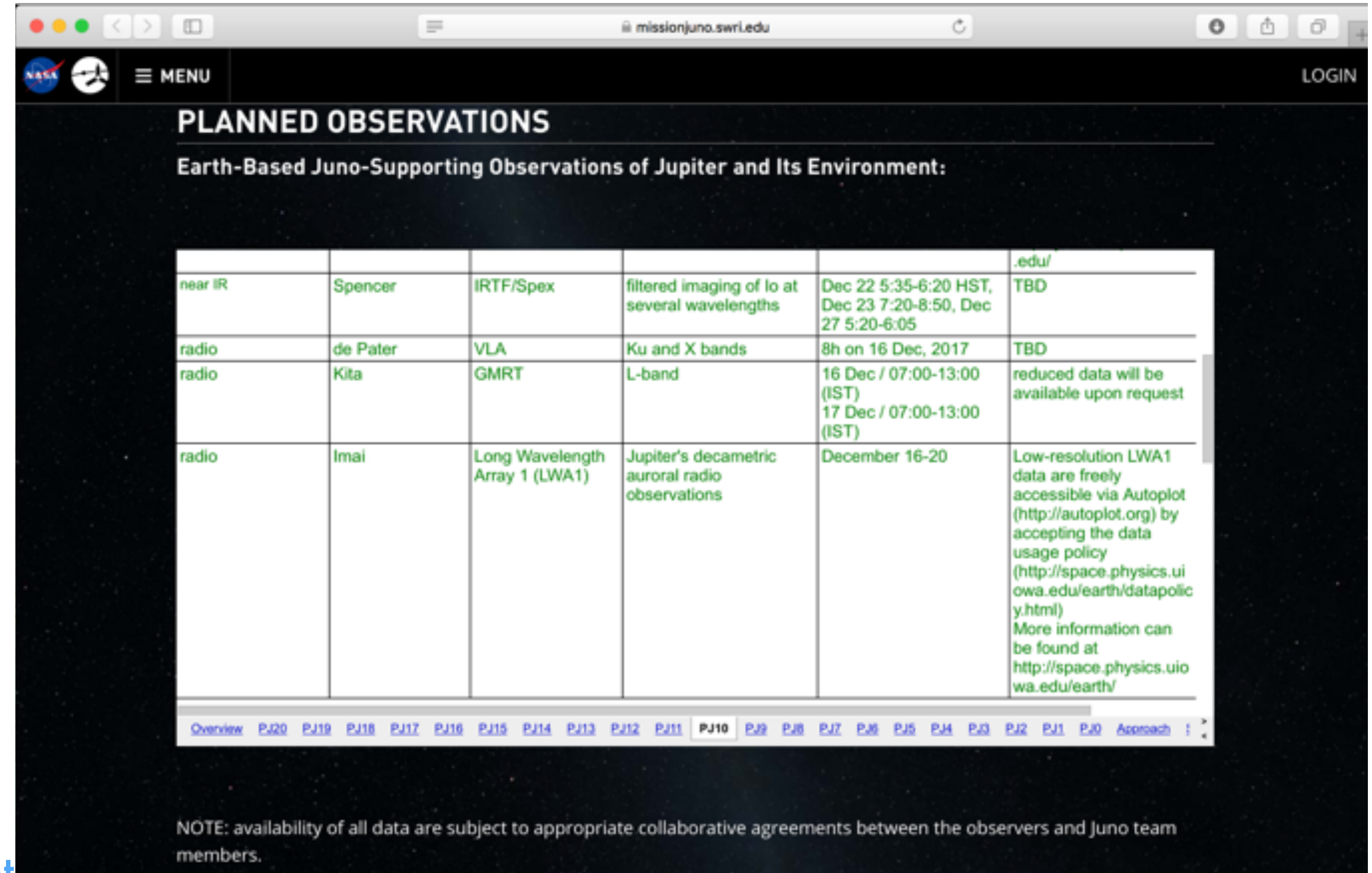
[Girard+, A&A, 2016]

Jovian synchrotron emission

- VLA (PI: I. de Pater) + VLITE (PI: T. Clarke), LOFAR (PI: D. Santos-Costa), & GMRT (PI: H. Kita)

Earth-based Jovian radio observations in concert with Juno





PLANNED OBSERVATIONS

Earth-Based Juno-Supporting Observations of Jupiter and Its Environment:

					.edu/
near IR	Spencer	IRTF/Spex	filtered imaging of Io at several wavelengths	Dec 22 5:35-6:20 HST, Dec 23 7:20-8:50, Dec 27 5:20-6:05	TBD
radio	de Pater	VLA	Ku and X bands	8h on 16 Dec, 2017	TBD
radio	Kita	GMRT	L-band	16 Dec / 07:00-13:00 (IST) 17 Dec / 07:00-13:00 (IST)	reduced data will be available upon request
radio	Imai	Long Wavelength Array 1 (LWA1)	Jupiter's decametric auroral radio observations	December 16-20	Low-resolution LWA1 data are freely accessible via Autoplot (http://autoplot.org) by accepting the data usage policy (http://space.physics.uiowa.edu/earth/datapolicy.html) More information can be found at http://space.physics.uiowa.edu/earth/

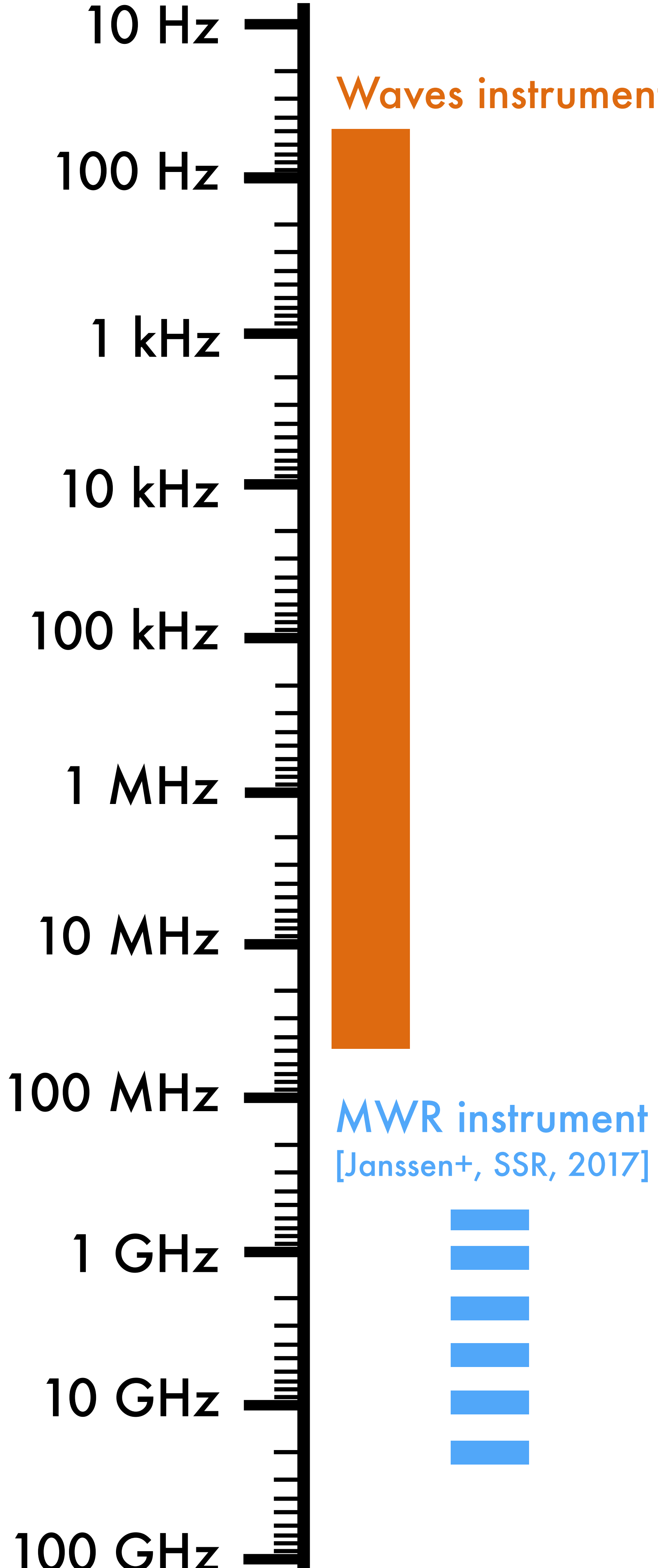
Overview PJ20 PJ19 PJ18 PJ17 PJ16 PJ15 PJ14 PJ13 PJ12 PJ11 PJ10 PJ9 PJ8 PJ7 PJ6 PJ5 PJ4 PJ3 PJ2 PJ1 PJ0 Approach

NOTE: availability of all data are subject to appropriate collaborative agreements between the observers and Juno team members.

Overview of past, current, and future campaign

https://www.missionjuno.swri.edu/planned-observations

Earth-based Jovian radio observations in concert with Juno



(c) Amelia Carolina Sparavigna/NASA

If you are interested in gazing at Jupiter with your telescope and Juno, please let us know.

Coordinator for Earth-based observations in support of the Juno mission:
Glenn S. Orton

General or scientific questions in the radio field:
Masafumi Imai
http://space.physics.uiowa.edu/~masafumi/