Serendipity with Cygnus A

The Rewards of Looking Closely …

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Associated Universities, Inc.

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

Cygnus A – The Iconic FR2 Radio Galaxy

- Cygnus A is a nearby (z = 0.056, 1.094 kpc/arcsec, D ~ 238 Mpc) extraordinarily luminous radio galaxy.

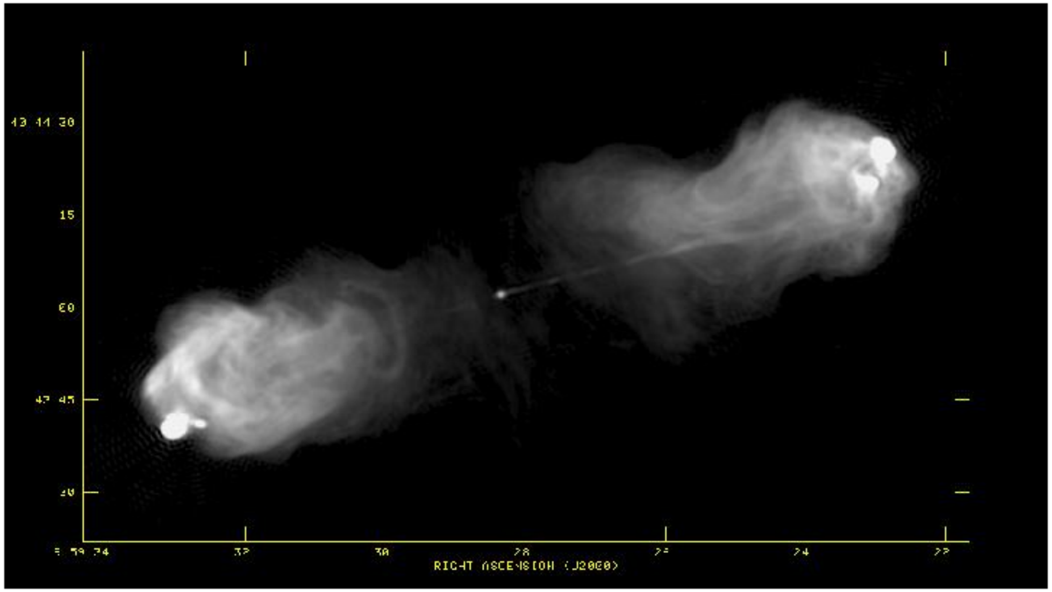
$$L_\upsilon \sim 10^{35} \ \text{erg s}^{-1} \ \text{Hz}^{-1}$$

$$L \sim 10^{45} \ \text{erg s}^{-1}$$

$$S_\upsilon \sim 1500 \ \text{Jy at 1.4 GHz}$$

$$E \sim 10^{60} \ \text{ergs}$$

$$P \sim 10^{-9} \ \text{ergs cm}^{-3}$$



110” ~ 120 Kpc

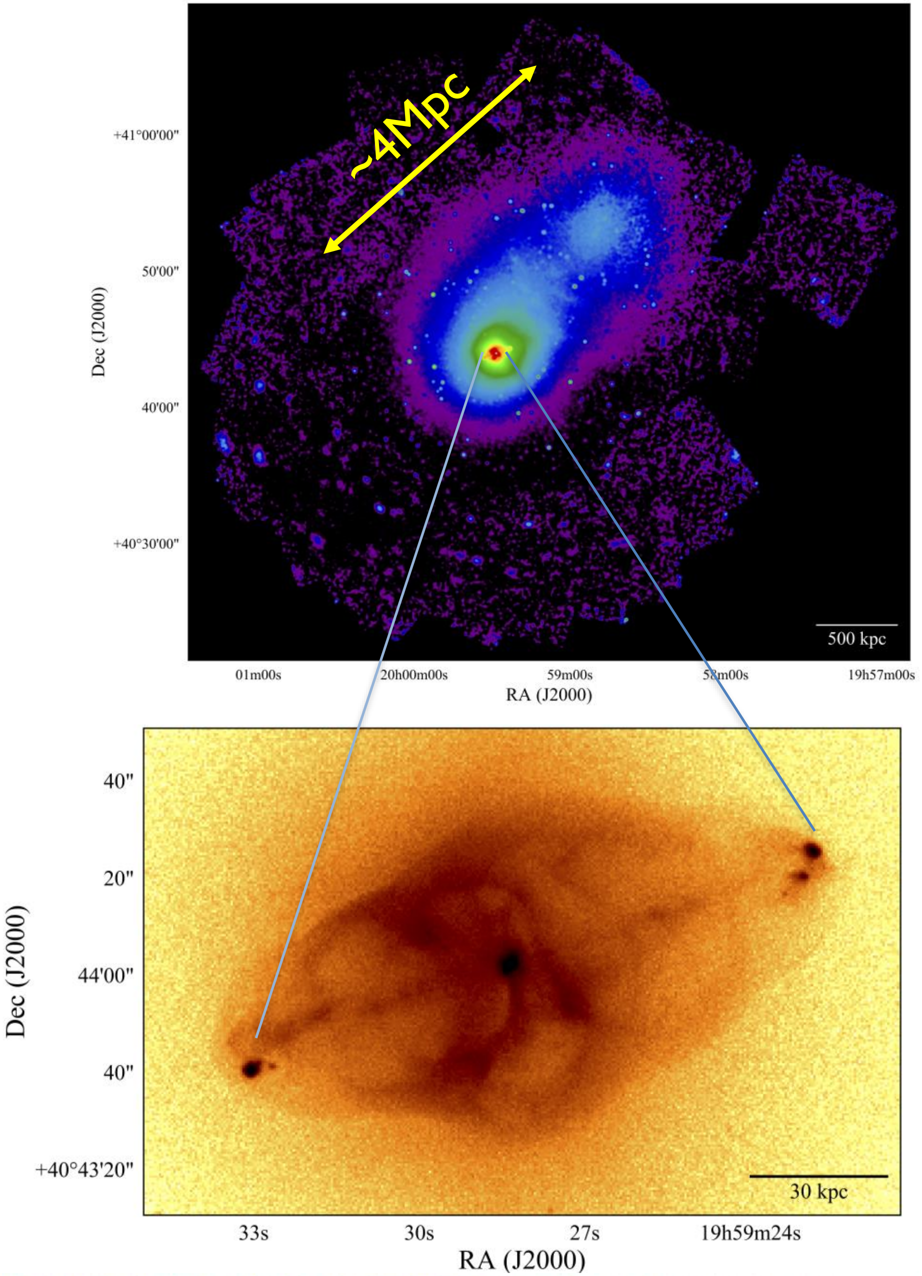
- Major radio components: Lobes, terminal hotspots, jets, and central nucleus.
- Emission mechanism is synchrotron – microgauss fields and relativistic particles.

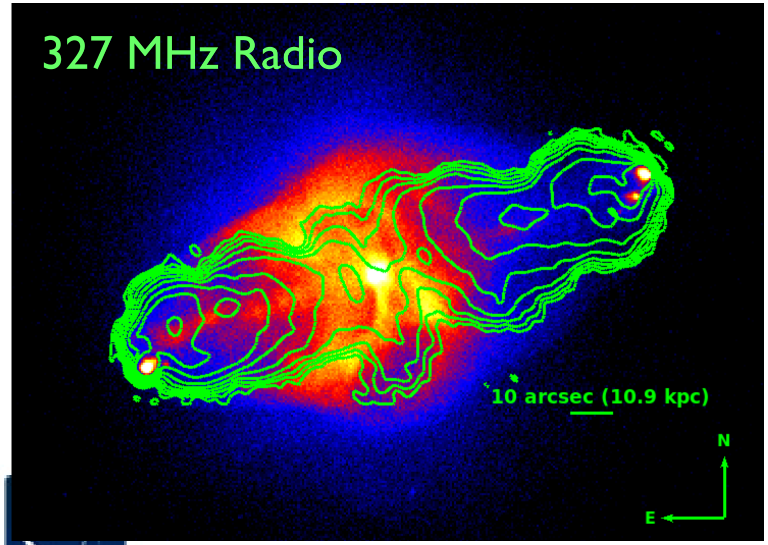
- It is amongst the most luminous of all objects in the universe:
- Due to its relative proximity, the spectral flux density is the highest (at cm wavelengths) of all sources.
- Relatively small angular size means the source is **bright**.

Cygnus A – X-Ray

- Cygnus A is embedded in a hot, dense, magnetized cluster:
  - $N_e \sim 4\ \mathrm{x}10^{-2}\ \mathrm{cm}^{-3}$,
  - $T \sim 2.5\ \mathrm{x}\ 10^{7}$ K (6 keV)
  - $M \sim 2\mathrm{x}10^{14}\ M_o$
- Shown here: Chandra Images

  Credit: Michael Wise, Ryan Duffey





The (Old) VLA Cygnus A Program

- In 1970s (before VLA was built), a basic picture of radio galaxy/quasar formation/evolution was accepted:
  - Central condensed object (BH?) origin of the power
  - Directed flow (EM beams? Jets? e-e+, p?) outwards
  - Shocks upon impact on undisturbed external medium
  - Waste gas inflated cavities, filled with left-over jet gas.
  - Radio emission via synchrotron emission.

- With VLA completion in 1980, we started an observational campaign.
  - Find the predicted radio jet (not previously known)
  - Resolve structures of hospots, lobes, nucleus, jets
  - Determine magnetic fields (intensity, structure)
  - Unravel the mystery of the 'anomalous depolarization' of Cygnus A.
  - Use synchrotron spectral aging analysis to understand evolution of the source.
- Results published in series of papers, 1984 through 1999.

Key VLA Results …

- Jets and filamentary lobe structure (Perley, Dreher, Cowan 1984)
  - This result a direct consequence of new method of **self-calibration**.
- **Extraordinary Faraday Rotation (Dreher, Carilli, Perley 1987)**
  - Cluster gas magnetized, 2 – 10 μG, organized on scales 20 – 30 kpc
  - No evidence for thermal gas in lobes: $n_e < 4\times10^{-4}$ cm^{-3} (5% of cluster)
- Bow shock discovered (Carilli+ 1988)
  - Proved the hotspot is expanding supersonically into the cluster gas.
- Detailed spectral aging (Carilli, Perley, Dreher, Leahy 1991)
  - Source age ~ 30 Myr. Hotspot spectra well fit by shock acceleration models.
  - Lobe spectral details incompatible with hotspots.
- X-ray imaging showed thermal gas influenced by radio (Carilli+ 1994)
  - Radio lobes have evacuated the thermal cluster gas
- X-ray hotspots found coincident with radio hotspots (Harris+ 1994)
  - Due to synchrotron self-Compton – fields close to ME if no protons.
- High Frequency hotspot spectrum (Carilli+ 1999).

Then, the effort stalled …

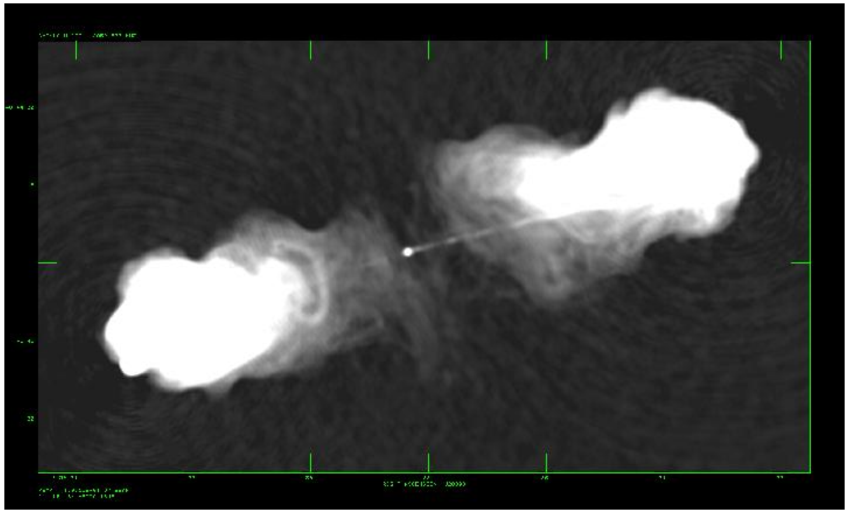
- The 'paper trail' dies away at this point in time.
- No additional VLA observations of Cygnus A after 1997, until 2014.
- Nothing else to be done (in radio) – we moved to other projects …
- But: much remains poorly understood:
  - How 'empty' are the radio lobes? 10%, 1%, 0.1% of the exterior?
  - Do any of the polarization effects (rotation measure) originate from the lobes? How much from any interaction zone between the lobes and cluster?
  - Why are the radio jets so dim? What (if any) relation is there between the radio jets and the X-ray 'jets'?
  - What is the detailed structure of the radio jets? How do they evolve as the jet expands outwards?
  - What is the relationship between the X-ray emission and the ongoing radio activity?
- Answering these (and other) questions requires much more capable X-ray and radio telescope observations.

The VLA Upgrade (aka Jansky VLA)

- The VLA was completed in 1980, using 1970s technology.
  - No technical upgrades for 20 years, except new receivers.
- By 2000, vast improvements in observational capability were possible using new technologies, and the original antennas and infrastructure.
- From 2001 to 2012, VLA underwent a major upgrade (~$90M):
  - EVLA Project was a US-Canada-Mexico consortium.
  - Full frequency coverage from 1 to 50 GHz in 8 frequency bands.
  - Wideband (8 GHz max) digital correlator with unprecedented frequency resolution and flexibility
  - But – no additional antennas or baseline coverage.
  - Orders of magnitude improvement in sensitivity at high frequencies.
- **Time to observe Cygnus A again!**
- Two major proposals submitted (~2014)
  - X-ray Chandra (2 million seconds). (M. Wise, PI)
  - Radio JVLA (44 hours). (R. Perley, PI)

The JVLA Cygnus A Program

- The upgraded VLA provides far more bandwidth and sensitivity than the old VLA.
- The new Cygnus A program has used about 44 hours of JVLA time with S, C, X, and Ku bands (2 – 18 GHz), and all four configurations.
- PIs are R. Perley, M. Wise, O. Smirnov, C. Carilli, R. Laing
- ~7 TB raw data.
- Goals include detailed polarization study of the lobes, a search for background objects, and detailed high resolution polarimetry of the jets.



Deep S-band image (2.0 GHz) showing details of the faint emission.

- We are currently focused on polarimetry
- Lerato Sebokolodi, Rhodes U., South Africa

Calibration and Imaging

- Initial basic calibration.
- Flux density and polarization angle based on 3C286.
- Polarization calibration used J2007+4029

- **Self-calibration done for each spectral window to improve fidelity.**

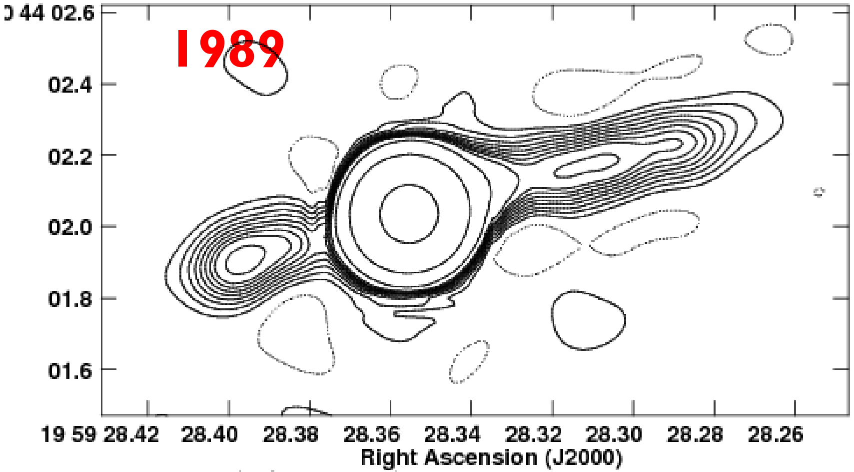
- Images made in Stokes I,Q,U, with channelization limited by:
  - Angular size (8 MHz) or
  - RM size (3 MHz at lowest frequencies).
  - >1000 independent frequency channels, between 2 and 18 GHz…
  - For > 1000 independent resolution elements…
- Highest resolution available to all frequencies is 0.7 arcseconds (700 pc).
- All calibration and imaging done in AIPS.
- All subsequent analysis done by Lerato Sobokolodi, using AIPS and external software.

Serendipitous Discoveries …

- During the process of imaging the Ku-band data (12 – 18 GHz, ~0.1 arcsecond resolution) for the polarization study, a remarkable, and completely unexpected feature was found:
    - **There is a new source of emission in the field, previously undetected.**
- And, in the process of better characterizing the emission from the new source, another unexpected discovery was made:
    - **There is a diffuse, elliptically-shaped, region of emission centered on the radio nucleus.**
- These 'serendipitous' discoveries underscore the usefulness of:
    - **Close 'human' inspection of imaging, particularly when utilizing instruments of greatly increased capability.**
    - **Utilizing all the modern tools for advanced imaging.**

A New Source Appears!

3C405 IPOL 8885.000 MHz CYG-X-1989.0.16.3



Peak flux = 1.0492E+00 JY/BEAM
Levs = 1.049E-03 * (-0.500, 0.500, 1, 1.500, 2,
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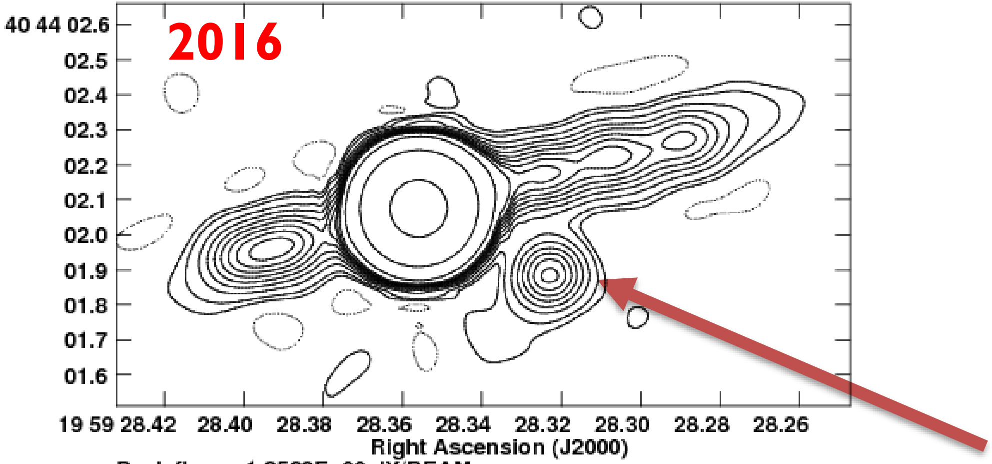
Cygnus-N IPOL 8424.000 MHz CYG-X-2015.0.16.3



Peak flux = 1.3569E+00 JY/BEAM
Levs = 1.357E-03 * (-0.250, 0.250, 0.500, 1, 1.500,
2, 2.500, 3, 3.500, 4, 5, 10, 50, 500)

1989 VLA observation:

6 hours integration

8.88 GHz, BW = 50 MHz

Rms noise: 0.33 mJy/beam

Resolution: 0.25 arcsec

Same brightness contouring

Same resolution = 0.16 arcsec

2016 JVLA observation:

45 minutes' integration

8.49 GHz, BW=1000 MHz

Rms noise: 0.20 mJy/beam

New object: Pk = ~5 mJy/beam

0.4 arcseconds from nucleus

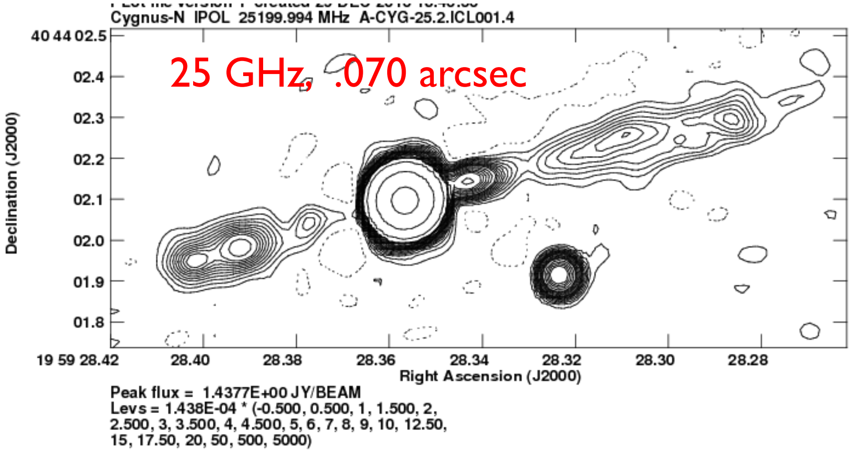
A Flurry of Activity …

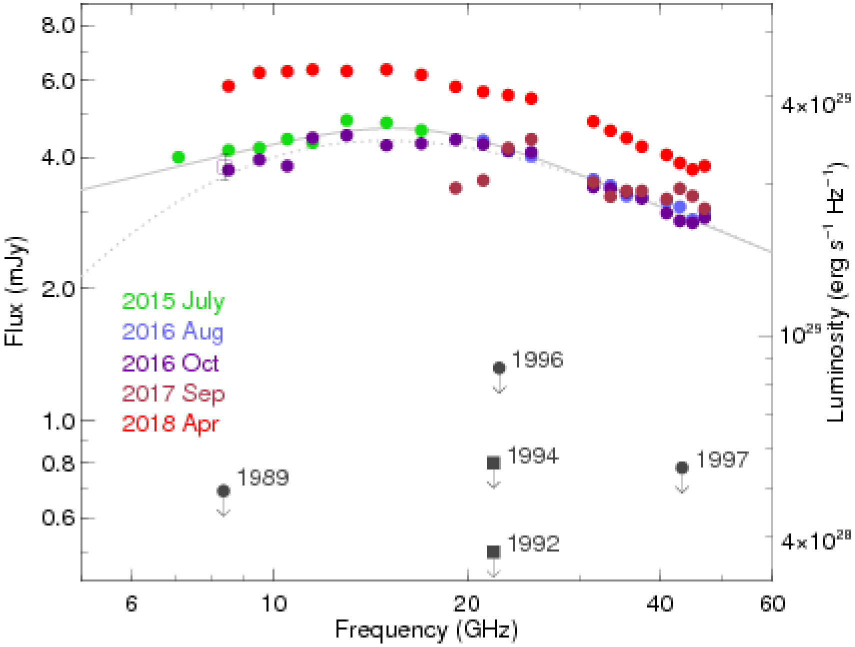
- This unexpected discovery initiated a flurry of activity:
  - VLA and VLBA 'DDT' observations and subsequent proposals – we have two epochs now at:
    - 8 to 48 GHz on the VLA (A and B configurations only)
    - 4, 7, 8.5 and 22 GHz on the VLBA
    - One more now scheduleld.
  - MERLIN observations at 1.4 and 4.8 GHz.
  - Observations by EVN at 5 and 22 GHz.
  - ALMA observations later this year or next

Flat-Spectrum, Brightened Fast, Still Rising (?)

VLA Observations were taken, in A and B configurations, in August and October, 2016, Sept 2017, and April 2018.

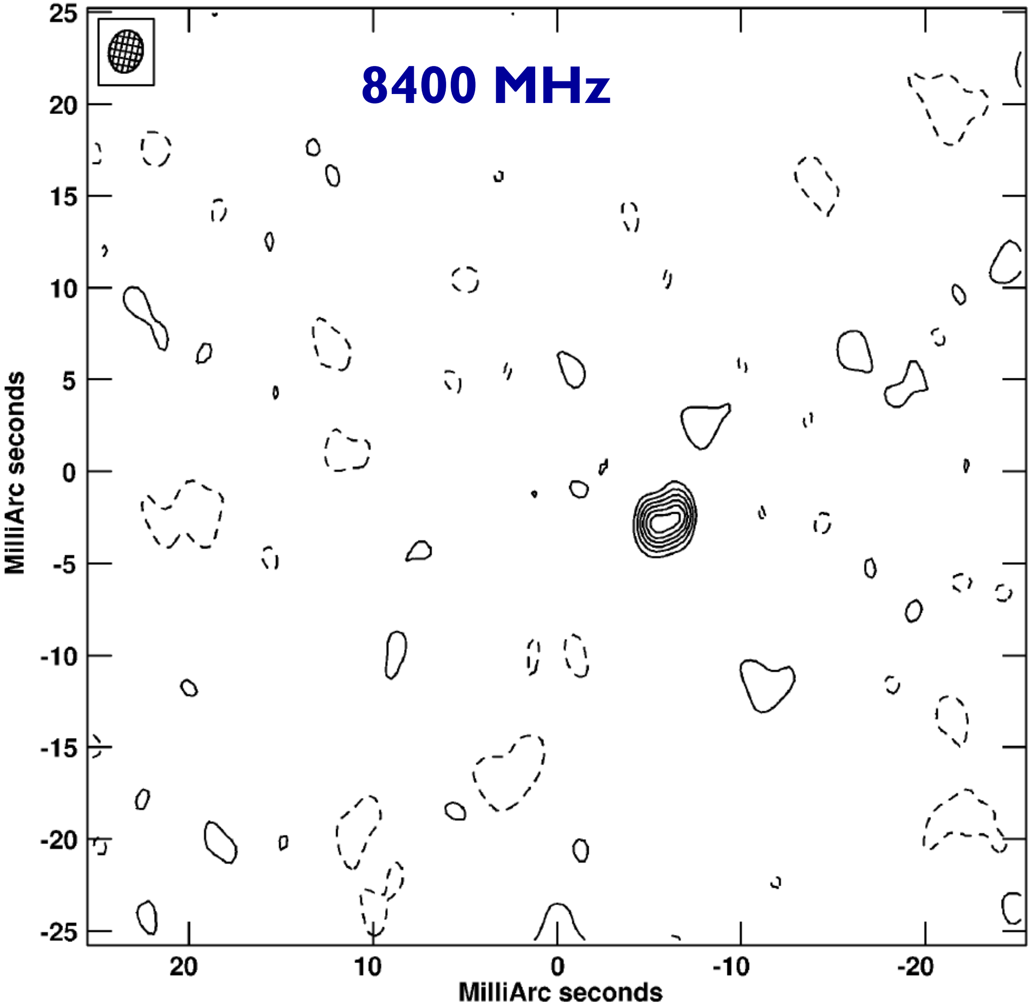
- The object has a flat spectrum, with low-frequency turnover below ~12 GHz.
- Possible increase in flux between 2016 and 2018
- Not detected at any time between 1989-1997 (Appeared rapidly sometime between 1997 and 2015)





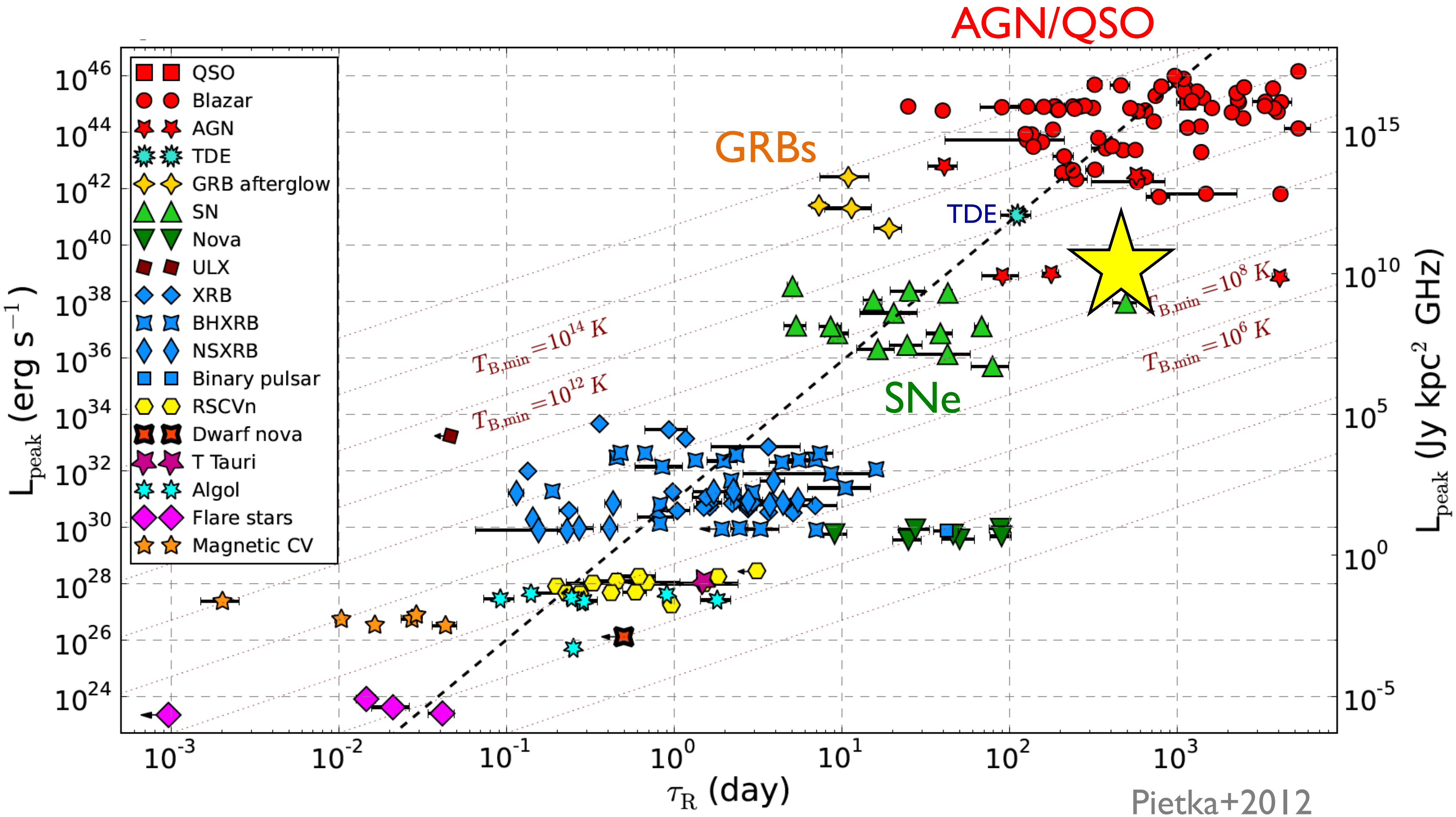
Detected, but unresolved (?), by VLBA

- We also obtained DDT time on the VLBA, at S and X bands.
- Slightly resolved? We ascribed this to ‘phase errors’.
- Angular size < 0.004 arcsec (<5 pc if inside Cyg A)
- Nonthermal ($T_b > 10^7$ K), but also not expanding superluminally
- Lack of scintillation indicates size > few hundred AU.



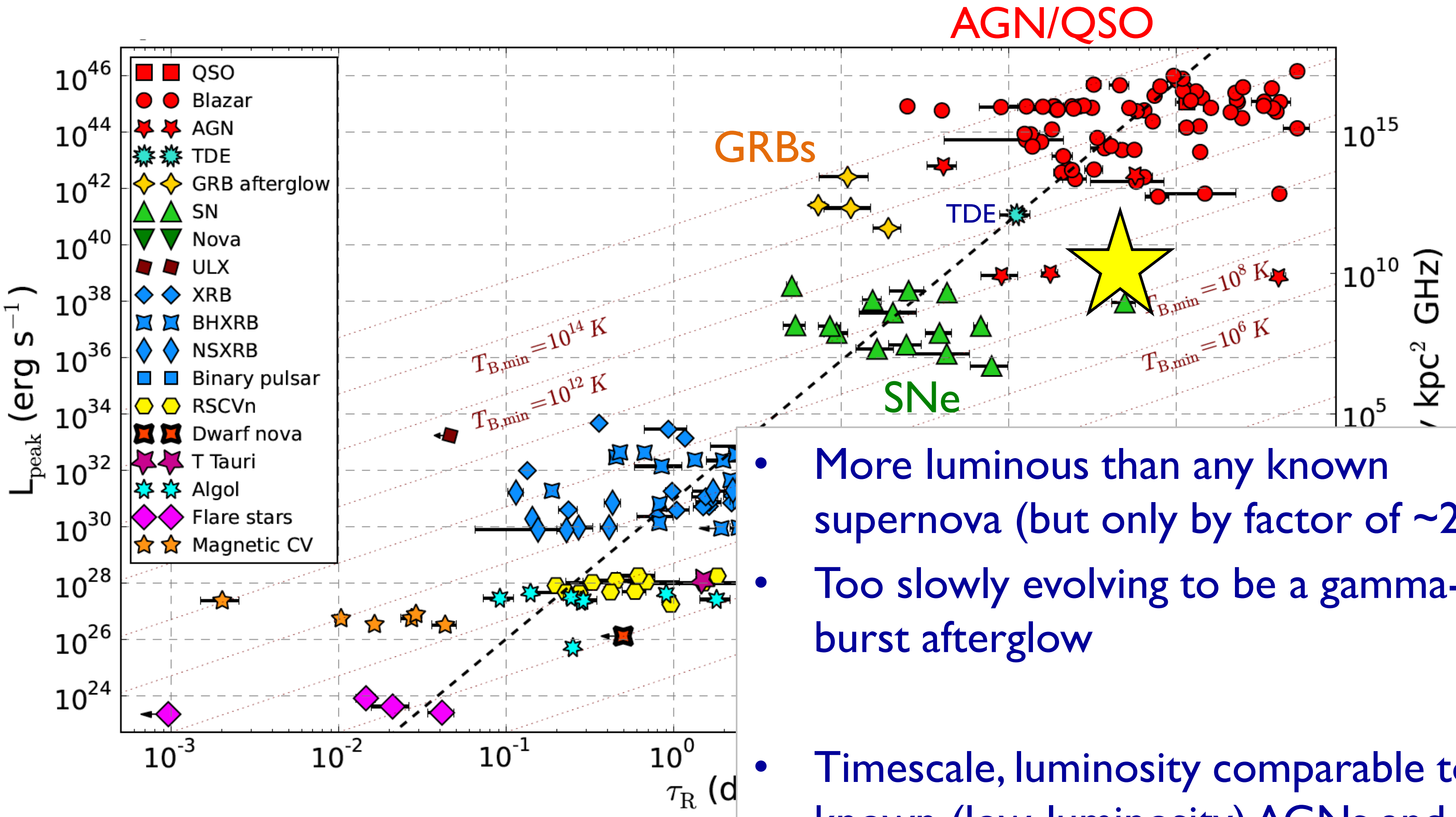
- Resolution: 2.3 x 1.8 mas @ -12

A Luminous Radio Transient



Pietka+2012

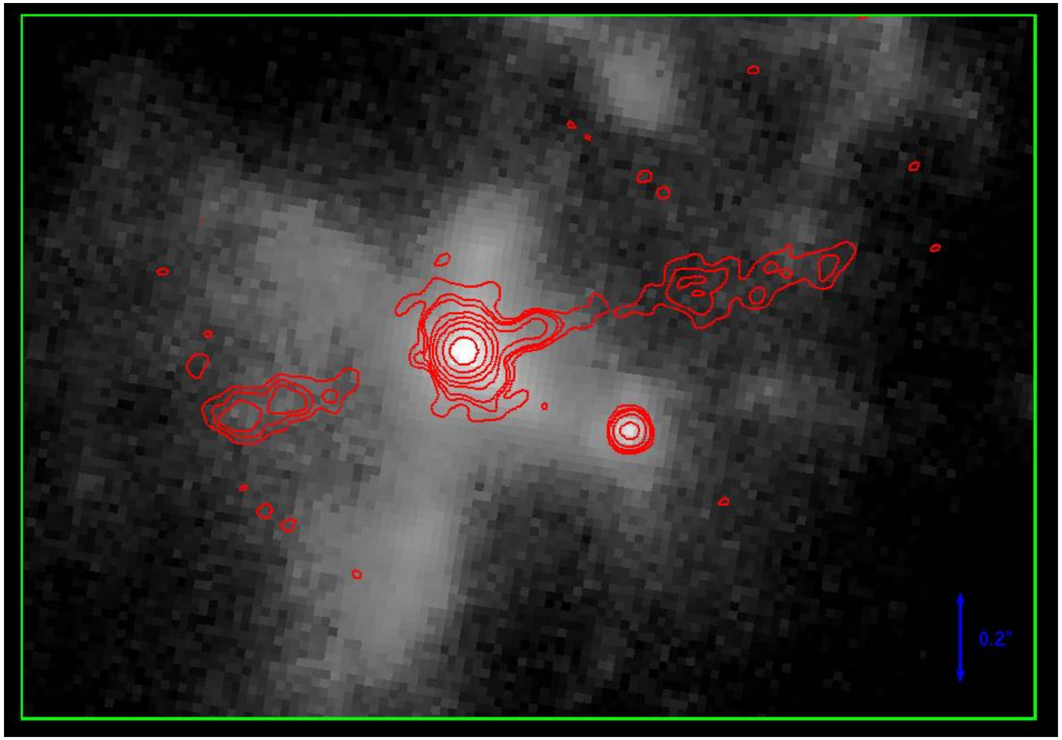
A Luminous Radio Transient



- More luminous than any known supernova (but only by factor of ~2)
- Too slowly evolving to be a gamma-ray burst afterglow
- Timescale, luminosity comparable to known (low-luminosity) AGNs and tidal disruption events

Pre-existing near-infrared counterpart

- An NIR point source at the same location was discovered in 2002 with adaptive optics + HST (Canalizo et al. 2003)
- Interpreted by them as a stripped galaxy core (old stars)
- Spectrum not definitive (dominated by scattered light from Cyg A nucleus)
- Radio detection, unresolved nature suggests instead that NIR+radio emission from the same, compact source



2μm image (AO)
35 GHz contours

Interpretation (D.A. Perley et al., 2017)

A Binary SMBH (AGN or TDE)

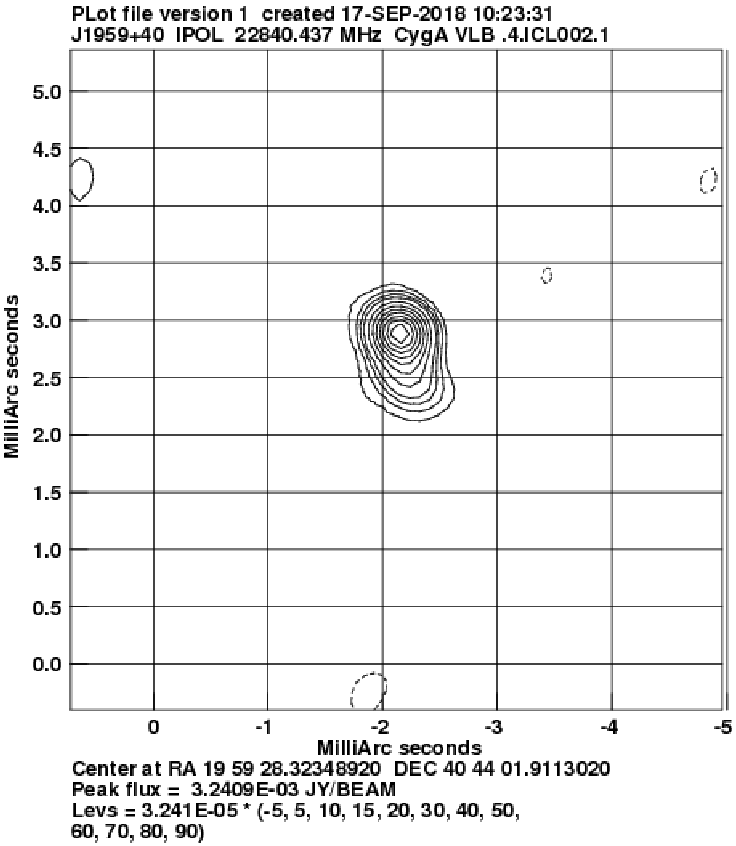
- Luminosity, timescale, spectrum, IR counterpart all consistent with a flaring/brightening **secondary** supermassive black hole in Cygnus A.
- Also consistent with theoretical expectation that luminous AGNs/QSOs are produced by merger activity. (Little direct evidence of a recent merger in this system until now).

Alternative model: a supernova?

- Cyg A nucleus does contain abundant star-formation
- Even so, would have to be the most luminous radio SN of all time – statistically unlikely?
- No simple explanation for IR counterpart (no bright star-formation lines)
- Lack of present time/SED evolution is also surprising

But there is more to the story …

- We have just completed analysis of new VLBA observations at C and K bands.
- Shown here is the 23 GHz image at 0.4 mas (0.4 pc) resolution.
- Summed flux 4.1 mJy (about right)
- Consistent with two components:
  - Unresolved 'core' < 0.1 mas
  - Southern extension ~ 0.4 mas size and offset.
- But the trouble is --- the location of this component is not quite the same as the X-band image shown earlier …
- It all becomes clear when matching to the C and newly-processed X-band data...



- Offset from nucleus:

$\Delta \alpha$ = -377.1 marc

$\Delta \delta$ = -182.1 marc

It’s a Double!!!

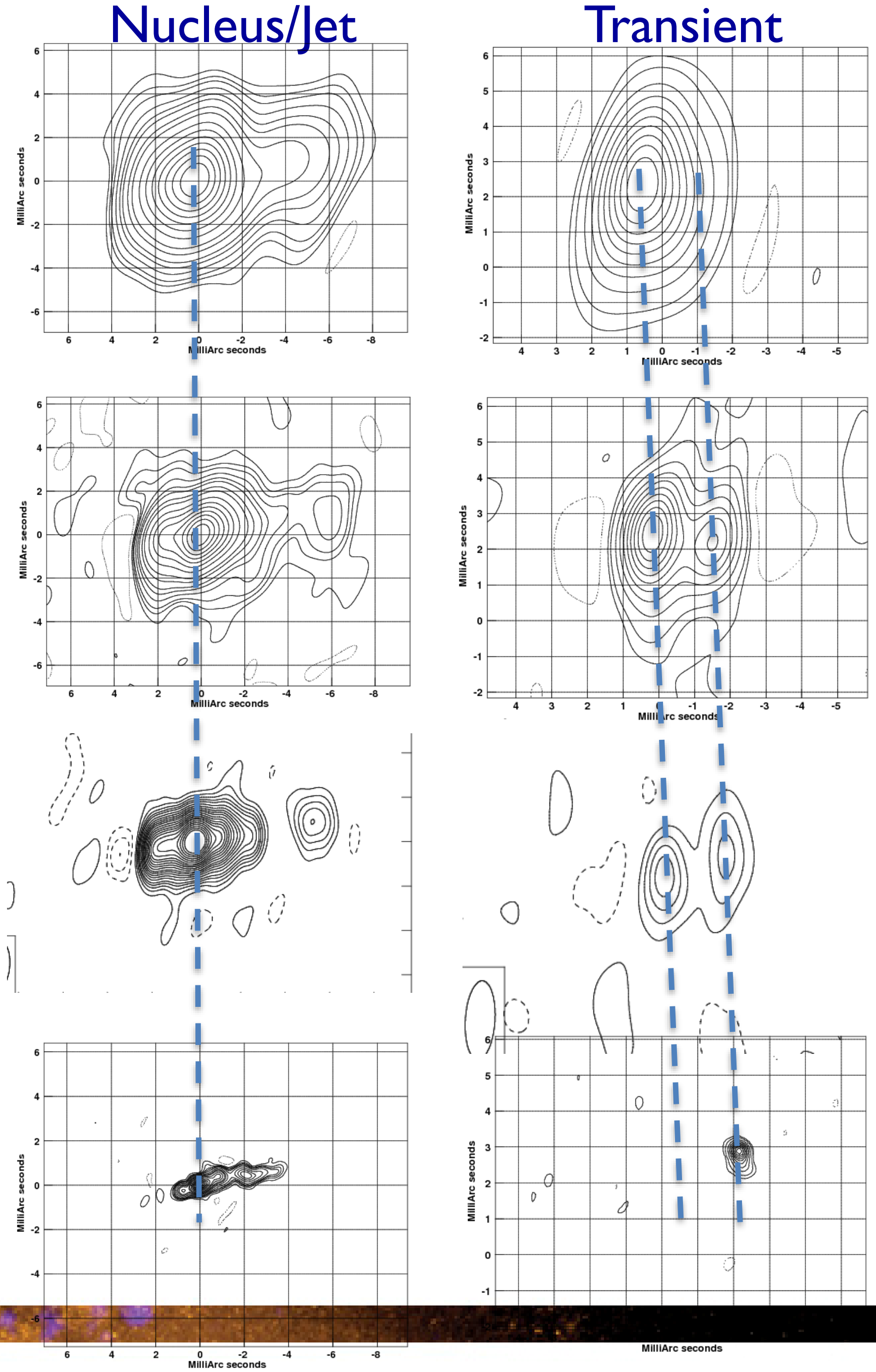
- The new observations, and reanalysis of the old X-band results, show the transient is a double!
- Separation 1.5 mas (1.6 pc)
- Slight frequency-dependent shift due to core opacity.
- East component has steep spectrum, west component inverted.

4700 MHz
3.5 x 1.7 mas
Dec 2017

7500 MHz
2.3 x 1.2 mas
Dec 2017

8400 MHz
1.9 x 0.7 mas
Nov 2016

22500 MHz
0.4 x 0.4 mas
July 2018



More Likely …

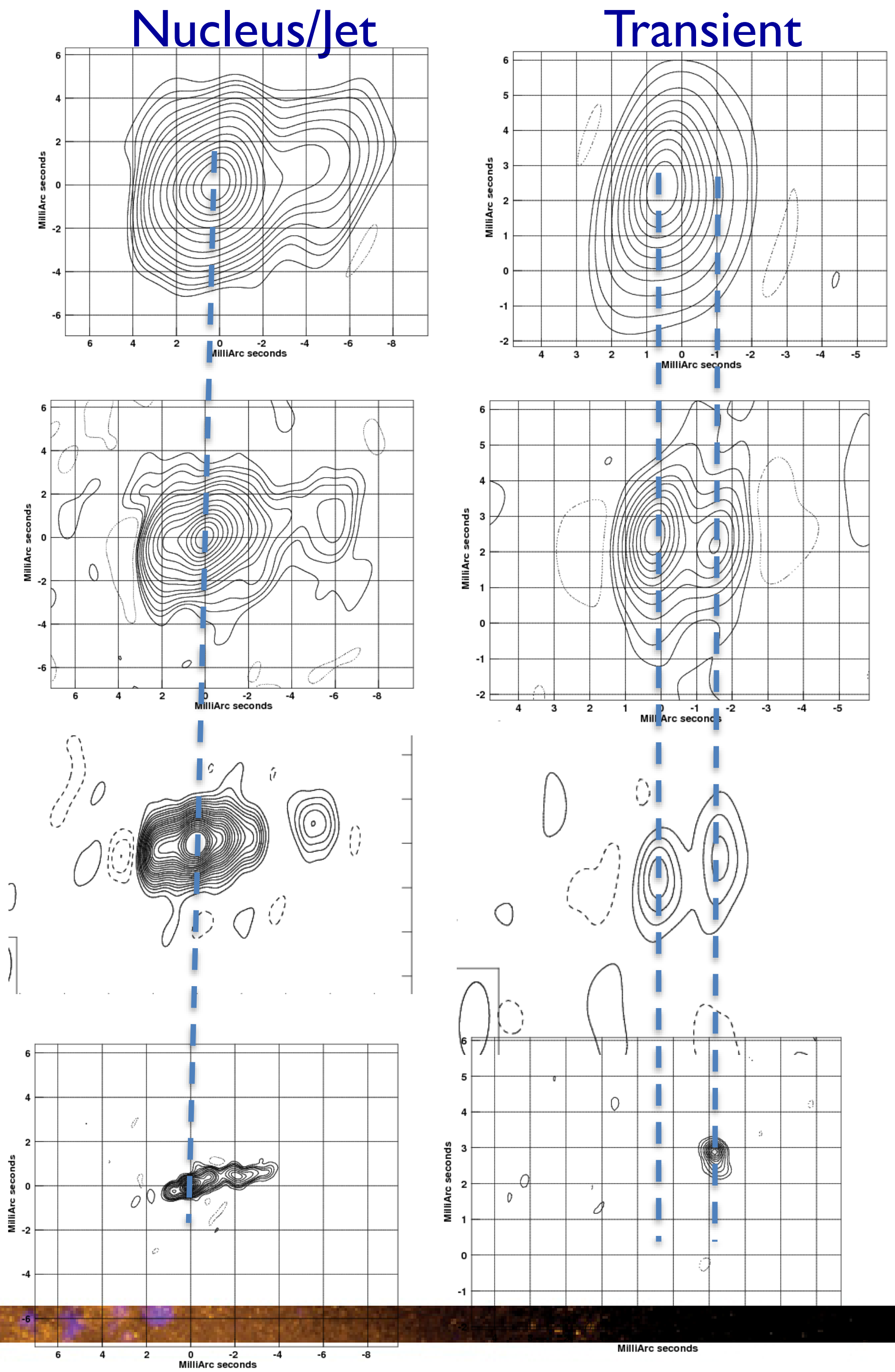
- **The Alternate Interpretation:**
- The right hand transient component has not moved.
- The Cygnus A nucleus shifts westward with longer wavelength.
- Why?
- Opacity would do this, if a dense ionized cloud lies on the eastward side.

4700 MHz
3.5 x 1.7 mas
Dec 2017

7500 MHz
2.3 x 1.2 mas
Dec 2017

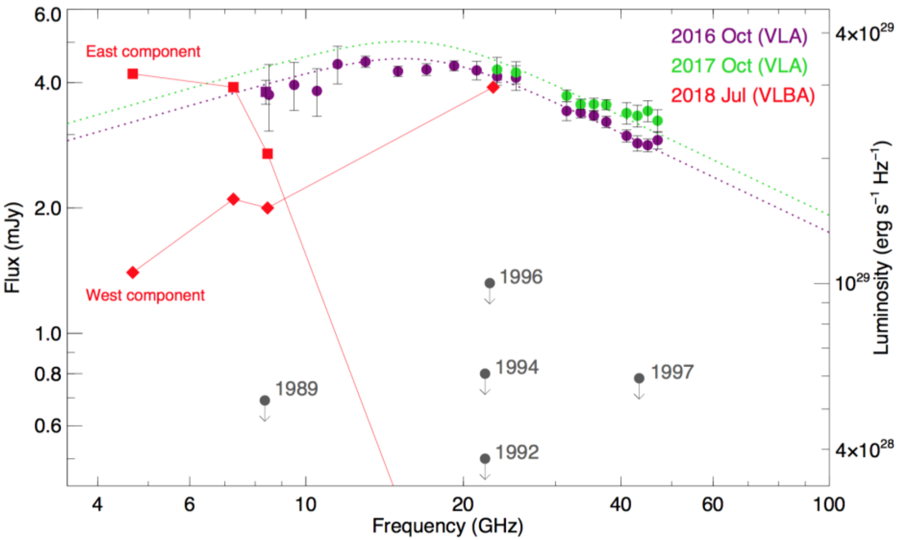
8400 MHz
1.9 x 0.7 mas
Nov 2016

22500 MHz
0.4 x 0.4 mas
July 2018



Strange Spectral Properties

- The disappearance of the eastern component of the transient is very odd.
- The spectra of the two sources show very different components:
  - The western component has an inverted spectrum – consistent with an optically thick nucleus
  - The eastern component has a normal steep-spectrum, except there must be a cutoff about 9 GHz.



- If the spectral cutoff of the eastern component is real, then the B-fields must be very high…

What to do? Get More Data!

- Hypothesis: Western component is the re-energized nucleus, the eastern component is a jet – which must have very high fields to extinguish the radiation above 9 GHz.
- If so, then the steep spectrum component should be a jet, or emitted component.
- Minimum apparent speed ~ 0.4c.
- Expansion should be measureable with VLBA over a few years.
- To check this, (and on the reality of this vanishing component), we have been granted 12 hours VLBA `DDT' time to re-observe at 8 GHz, and make new observations at 15 GHz.
- Stay Tuned!

But Wait! There's more!!!

- Imaging the highest resolution data (especially the 45 mas resolution data from 30 GHz) shows clear evidence of another, unexpected component.
  - Top: With the 1280 mJy nucleus present
  - Bottom: With 1277 mJy subtracted.
- The emission is seen in both epochs, and at all frequencies above 20 GHz. (Lack of resolution prevents clear detection below this frequency).

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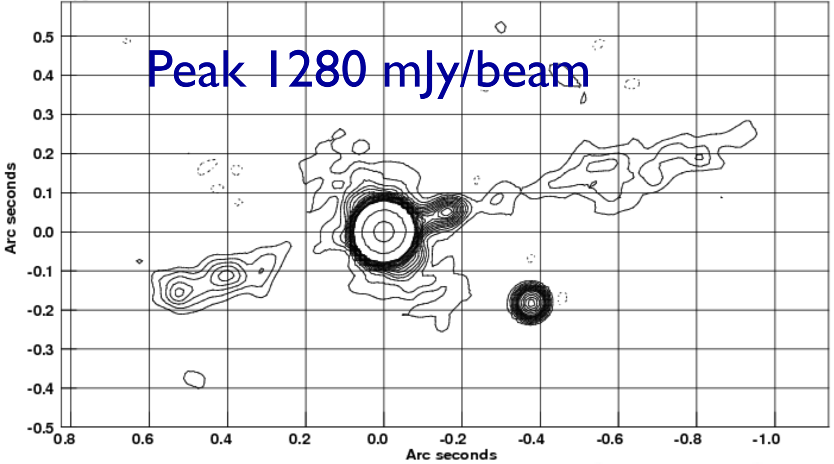

Center at RA 19 59 28.35663 DEC 40 44 02.0970
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Levs = 4.281E-05 * (-2, 2, 4, 6, 8, 10, 12.50, 15,
17.50, 20, 22.50, 25, 30, 40, 50, 60, 70, 80, 90,
1495, 14950)

500 pc

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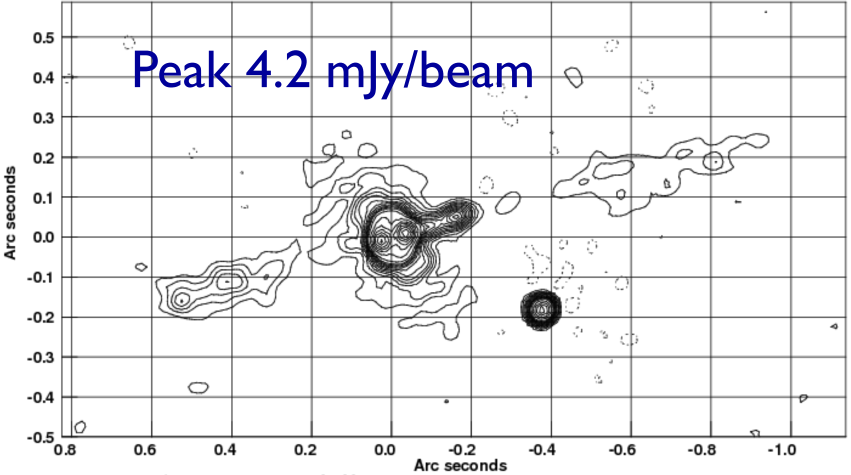

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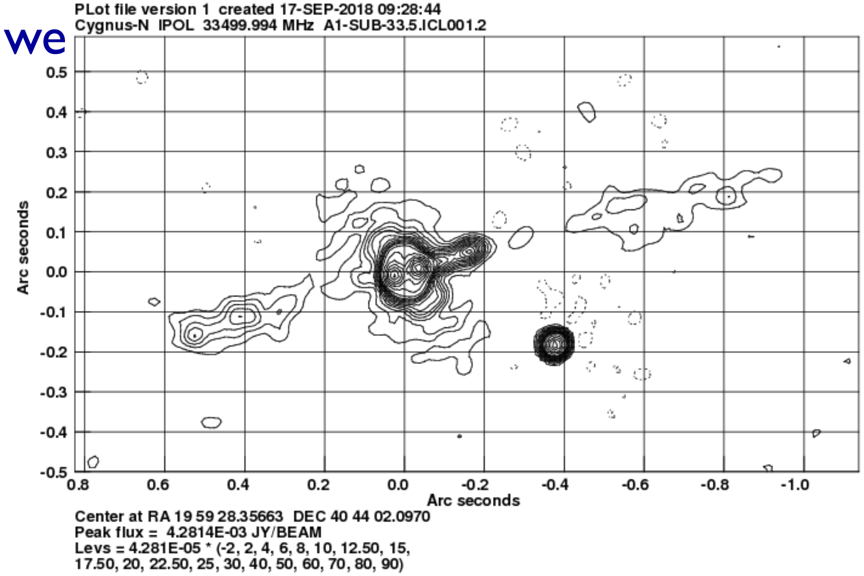
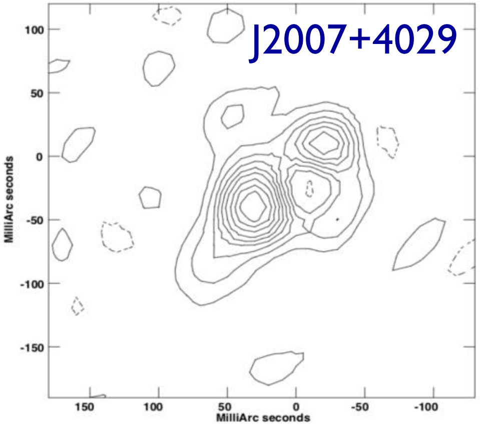
Levs = 4.281E-05 * (-2, 2, 4, 6, 8, 10, 12.50, 15,
17.50, 20, 22.50, 25, 30, 40, 50, 60, 70, 80, 90)

Can We Believe This Residual?

- It is reasonable to question the result – we are removing 99.8% of the peak, and claiming the residual is real…
- Evidence to support reality:
  - The same distribution is seen at all frequencies (20 – 48 GHz).
  - The residual brightness is physically reasonable.
  - The two little point-like components correspond exactly to the inner VLBI-scale jet.
  - Imaging of the calibrator (J2007+4029), which has the same flux density as the Cygnus A nucleus, shows (almost) no residual at all.



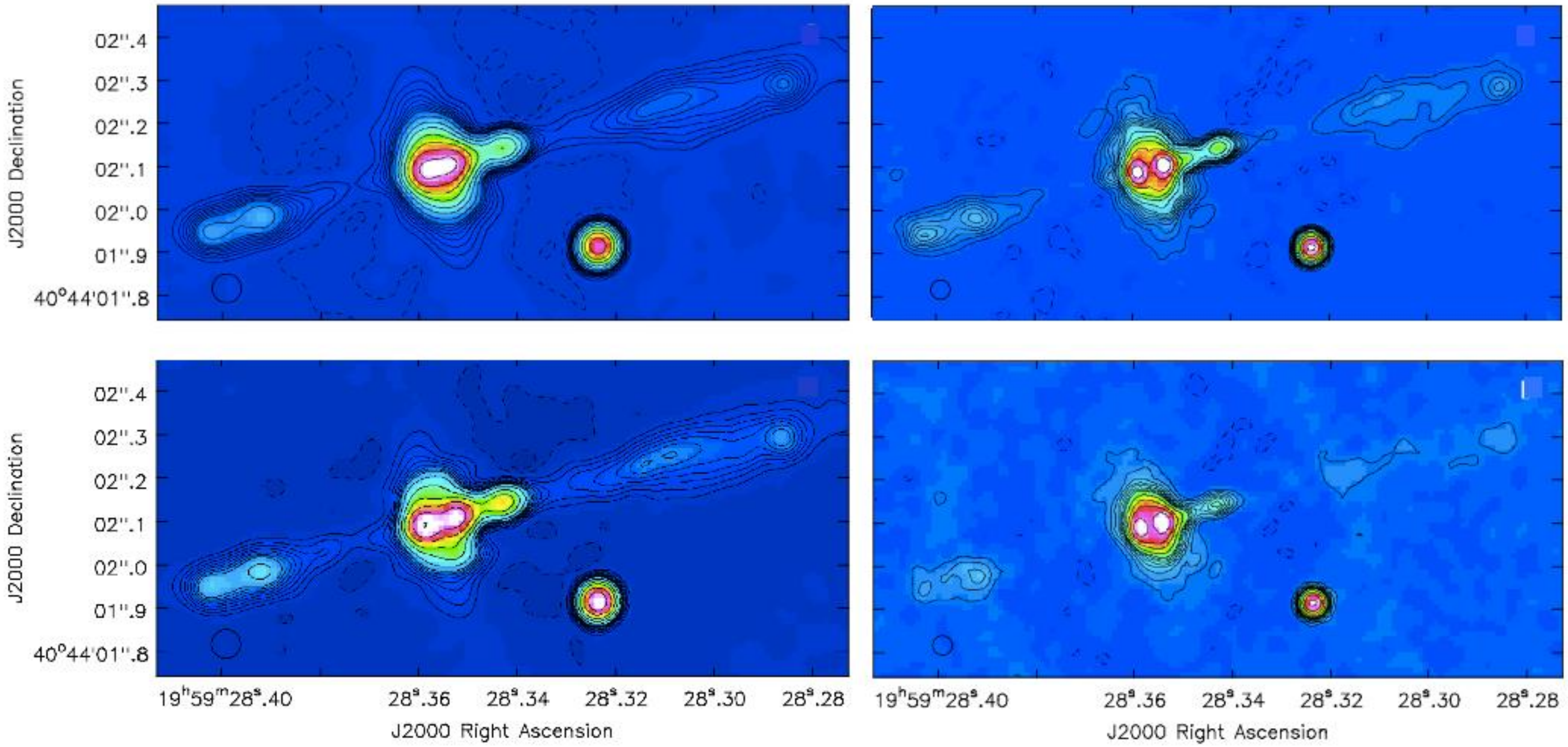


Same brightness contours

A nice representation …

All data (19 – 47 GHz), 67mas

34 GHz, 45 mas



22 GHz only, 67 mas

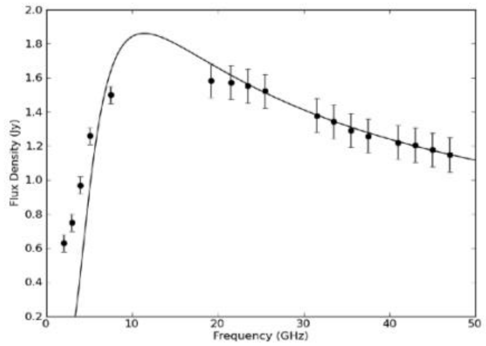
44 GHz, 45 mas

So – what have we found?

- There appears to be two different elliptical structures centered on the nucleus, and roughly perpendicular to the jets.
  - Inner: Diameter ~ 100 pc, T_b~ 800 K,
  - Outer: Diameter ~480 x 260 pc. T_b ~ 200K at 100 pc offset.
- The following analysis is based on the outer elliptical emission only, using the surface brightness at 100 pc.

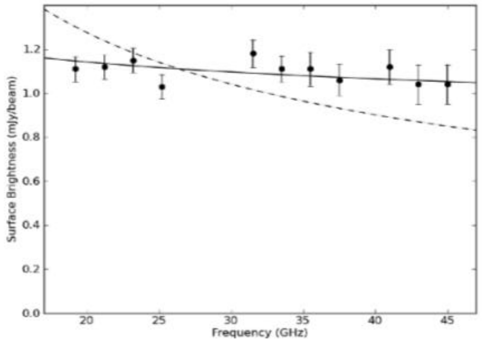
Spectrum of Nucleus and 'Torus'

- Nuclear emission shows a sharp turnover near 10 GHz
  - Model is from free-free absorption with observed EM
- 'Torus' spectra are flat, with different slope than nucleus.
  - Models are optically thin bremsstrahlung (solid) with α=0.1, and power-law with α~0.5 (broken)
- The free-free model is favored over an electron scattering.



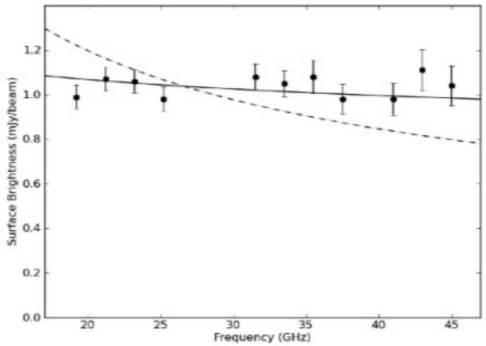
Nucleus

(2 – 47 GHz)



Torus north

(20 – 47 GHz)



Torus south

(20 – 47 GHz)

Physical Characterists

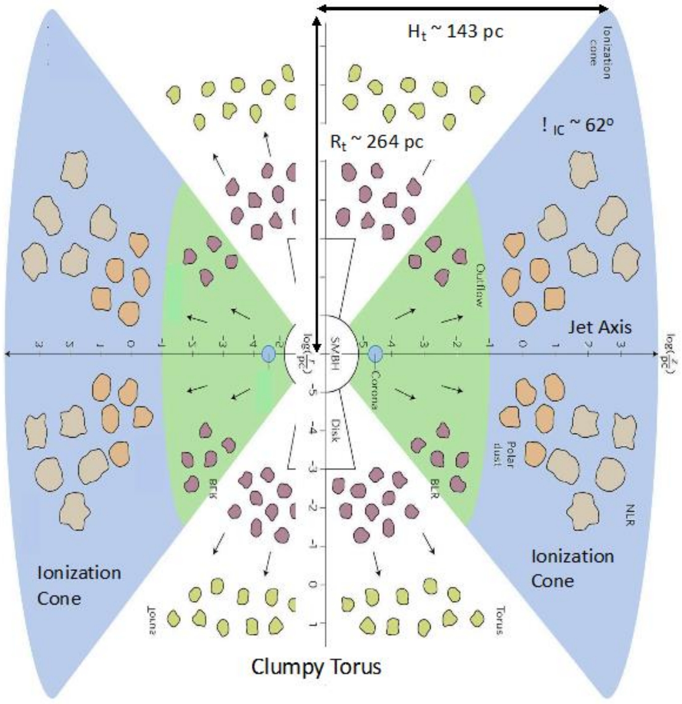
- Using the mean brightness of the outer emission (0.47 mJy/beam at 33 GHz), we find:
  - Tb ~ 240K
  - EM ~ 12.2 x 10^7 pc cm^{-6} (assuming $T_e = 10^4$K)
  - From this, the τ=1 frequency is 5.8 GHz, which could explain the spectral turnover of the nucleus.
- But this is not the only possibility:
  - VLBI observations show the nucleus has a sharply inverted spectrum between 22 and 43 GHz.
  - Likely due to SSA of the nucleus and innermost jets.
- We cannot at this time discriminate between these, and both might be involved.

A Simple Model

- Thick torus of obscuring material, perpendicular to jet.
- Using implied path length of 510 pc, and the observed EM, we find:

  $n_e \sim 490$ cm^{-3}.
- But this leads to a contradiction: the column density is then 4 x10^{23} cm^{-2}, leading to a Thompson scattering depth of $\tau \sim 0.26$.
- This predicts 170 mJy of scattered flux, but only 21 mJy is seen.
- Best solution is a clumpy medium.

  Enhances free-free emission (n_e^2), so majority of emission from regions with density > 4000 cm^{-3}.



Conclusions – and Future Needs …

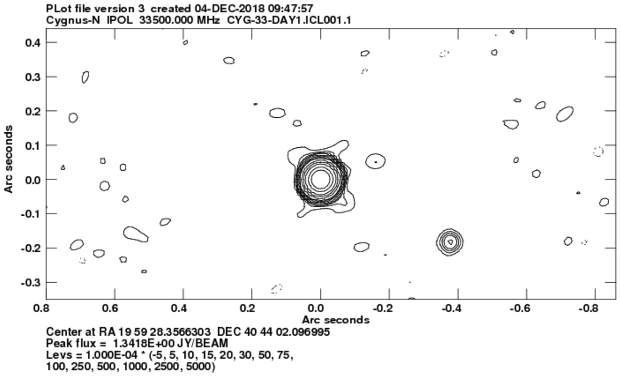
- We have discovered an elongated, flat-spectrum continuum emission region centered on the nucleus of Cygnus A.
- The physical scale is ~500 x 300 pc, with brightness temperature of ~ 250K. An inner, denser region is likely.
- Radio spectra consistent with free-free emission, and inconsistent with Thompson scattering and synchrotron.
- Analysis suggests the medium is likely clumpy, with the emission dominated by clumps with density ~ 4000 cm^{-3}.
- These results based on pushing the VLA to its current limits. Further, most exacting work will require an instrument with much higher resolution and sensitivity at these frequencies – the NGVLA!

Serendipity, or, the art of discovery

- These curious, perhaps important, discoveries, were the result of three factors:
  - New instrumentation, giving a sensitivity/resolution far higher than previous existed
  - Modern self-calibration methods, which remove the scattered emission from the bright nucleus
  - An experienced eye (mine, in this case), knowledgeable in the characteristics of the instrument and the expected 'normal' properties of the source.
- Which raises the question: Could the current JVLA (or any!) pipeline have seen, and recognized, these features?
- Note: Current pipelines do standard calibration, and standard imaging. No self-calibration, and no 'experienced eye' to review results.

What would the Pipeline show?

- To illustrate this point, I show what a standard calibration would have revealed.
- I contour these at a ‘normal’ level, appropriate for the noise.
- 2nd epoch much better image.
- Conclusion: The transient would have been visible (if anybody was looking), but the `torus’ would have been missed.



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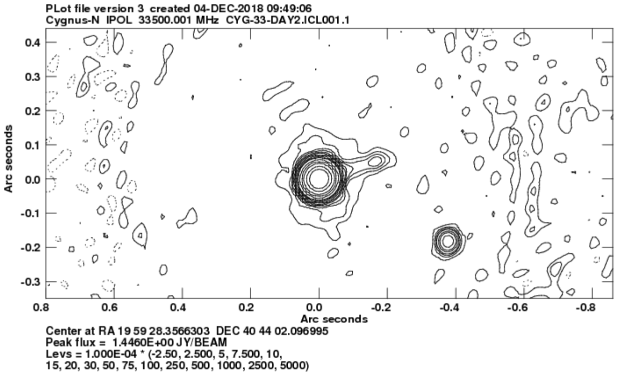
Center at RA 19 59 28.3566303 DEC 40 44 02.096995
Peak flux = 1.3418E+00 JY/BEAM
Levs = 1.000E-04 * (-5, 5, 10, 15, 20, 30, 50, 75,
100, 250, 500, 1000, 2500, 5000)

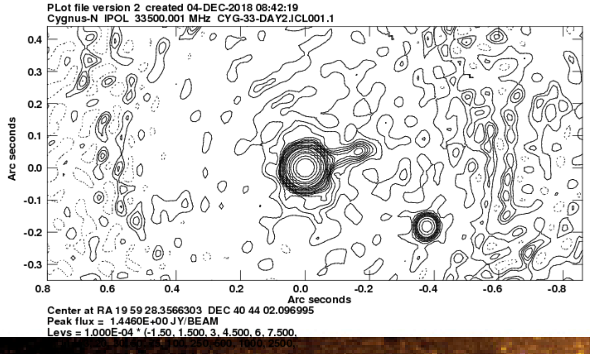
Oct
2016



PLot file version 3 created 04-DEC-2018 09:49:06
Cygnus-N IPOL 33500.001 MHz CYG-33-DAY2.ICL001.1

Center at RA 19 59 28.3566303 DEC 40 44 02.096995
Peak flux = 1.4460E+00 JY/BEAM
Levs = 1.000E-04 * (-2.50, 2.500, 5, 7.500, 10,
15, 20, 30, 50, 75, 100, 250, 500, 1000, 2500, 5000)

Apr
2018

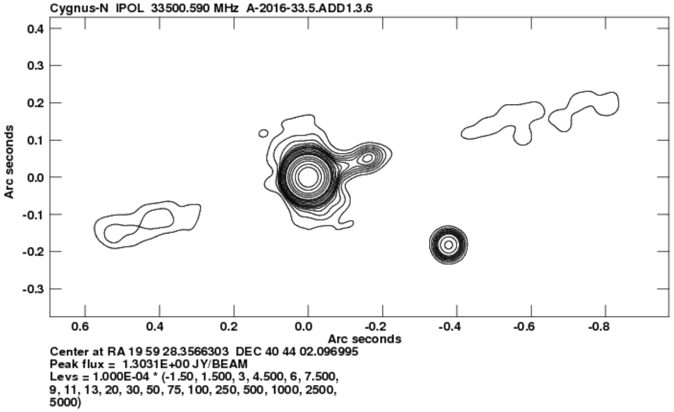


PLot file version 2 created 04-DEC-2018 08:42:19
Cygnus-N IPOL 33500.001 MHz CYG-33-DAY2.ICL001.1

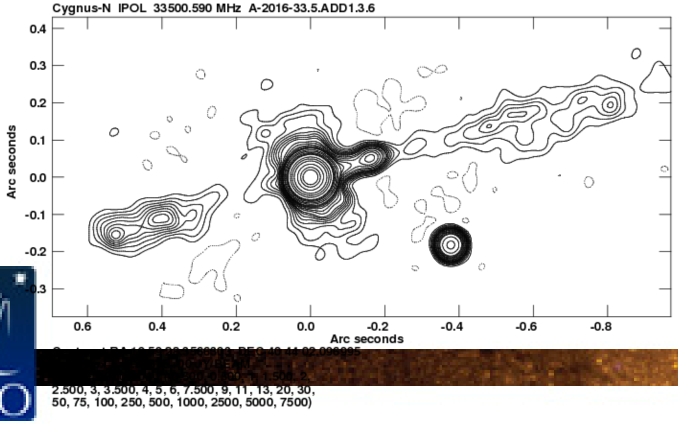
Center at RA 19 59 28.3566303 DEC 40 44 02.096995
Peak flux = 1.4460E+00 JY/BEAM
Levs = 1.000E-04 * (-1.50, 1.500, 3, 4.500, 6, 7.500,
[illegible] 20, 30, 50, 75, 100, 250, 500, 1000, 2500,

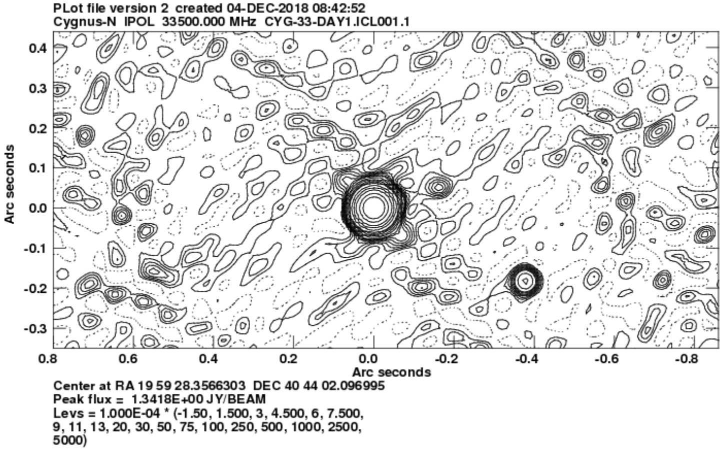
The Power of Self-Calibration

- Self-calibration is a powerful tool.
- None of the existing NRAO pipelines make use of it. To show the difference…



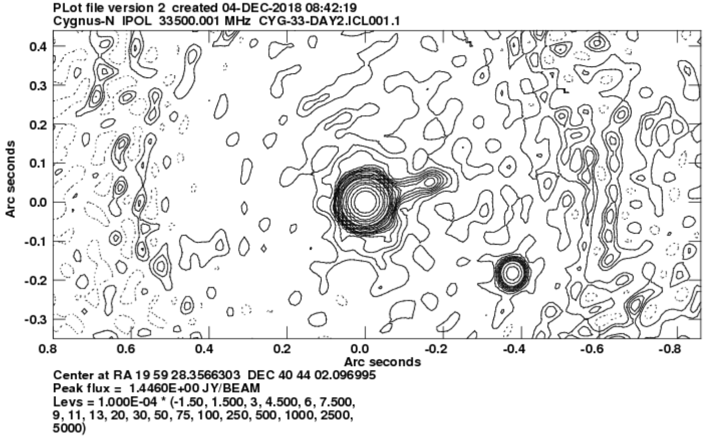
With Self Cal





Oct 2016

No Self Cal



Nov 2018

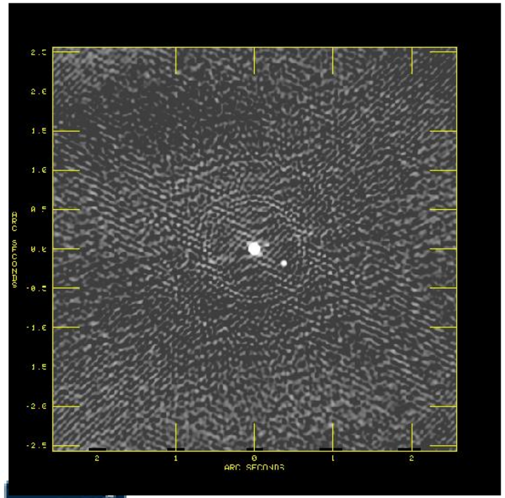
- More than 10X improvement.

A Grey-Scale Representation.

- Shown here are the two individual observations, and the 'best' image, all using the same greyscale wedge.

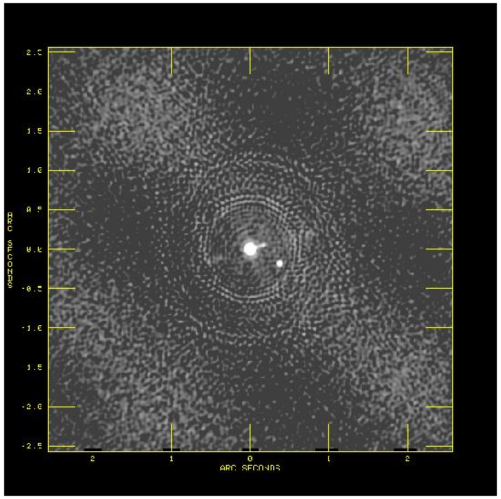
October 2016

No self-cal



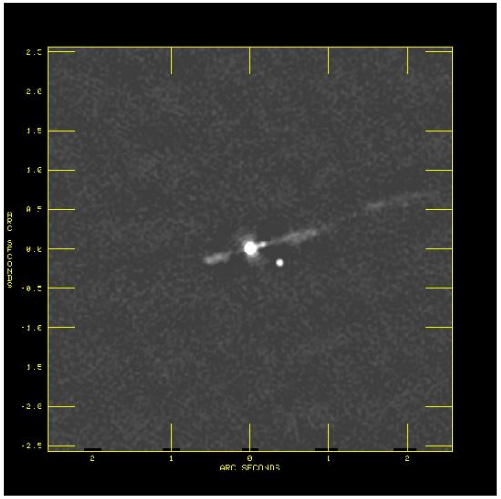
April 2018

No self-cal



Both

With Self-Cal



My Concerns…

- The new generation of astronomers are becoming more and more 'distant' from the telescopes they use, particularly the major facilities (VLA, MeerKAT, LOFAR, SKA, etc.)
- This is mostly not their fault – instruments are becoming bigger and bigger, and more and more complex.
- These (mostly inevitable) trends do not encourage astronomers to understand their instruments in reasonable depth.
- The problem is especially severe in synthesis imaging.
- It is thus no surprise that 'SRDP' ('Science Ready Data Products') is very popular amongst our users.
- A new NRAO division has been formed to develop SRDP
- I fear that as pipelines become faster and better (and they will), fewer and fewer 'eyes' will actually 'look' at what is produced.
- Images will go straight to some sort of processing, looking for a signature, or statistic which is essentially predefined.

My Concerns (cont.)

- This might be good (and necessary) for a lot of science, but the lack of:
  1. Advanced calibration methods (self-calibration, DDE calibration) means the quality of the images will nearly always be sub-optimum, and in many cases, quite terrible.
  2. The lack of 'experienced eyes' (or, perhaps, a smart machine) to recognize what is normal and what is not

Means that the real cool stuff – the stuff of surprise and discovery – is severely hampered, and may even be lost.

Is Discovery Hopeless? Is Serendipity Dead?

- I hope not. ☺
- People talk about machine learning. I'm aware that much effort is going into this field. Sounds good, and I hope my pessimism is unwarranted.
- But I suppose that if machines are going to be able to replace the experienced human brain in identification of 'interesting features' (which are not instrumental in origin, which nearly all of them will be so long as calibration is done the dumb way), machines will have to learn to work like an experienced human eye/brain.
- Retaining the benefits – and joys – of serendipitous discovery in the area of Big Science, is the responsibility of the upcoming generation.