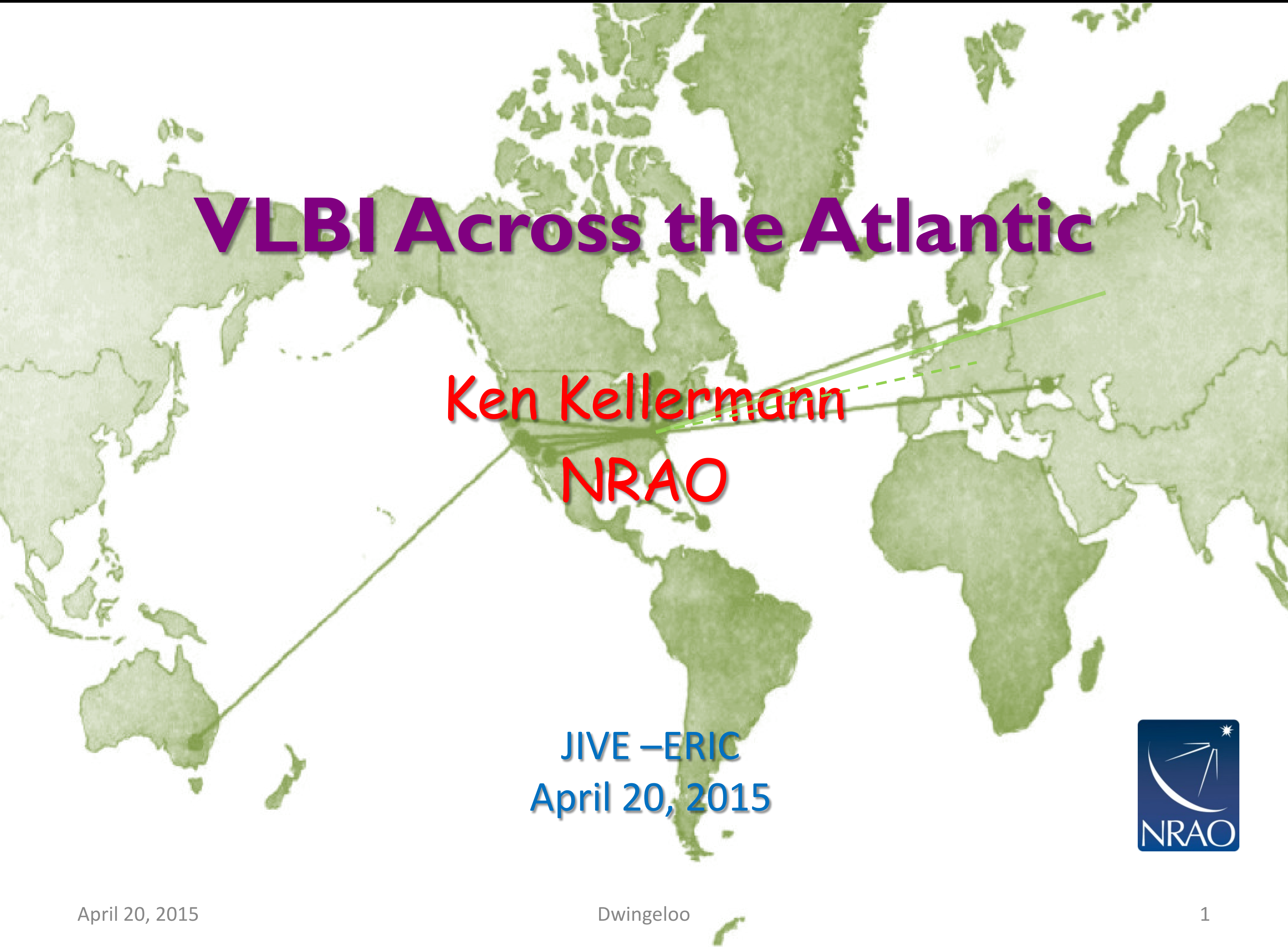


VLBI Across the Atlantic

Ken Kellermann
NRAO

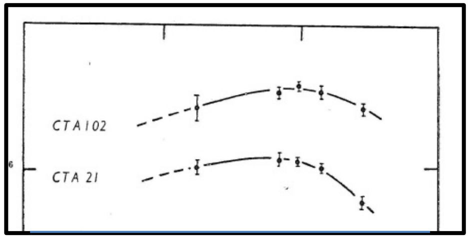
JIVE –ERIC
April 20, 2015

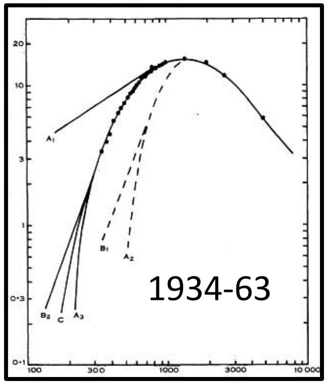
VLBI Across the Atlantic?

- VLBI over in the colonies?
- VLBI in Europe as seen from the colonies?
- VLBI as seen from an American in Europe?
- Transatlantic VLBI?

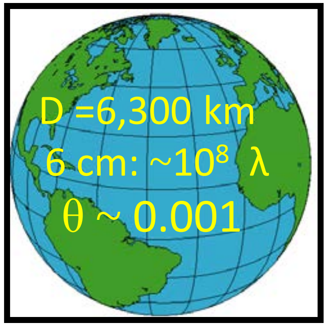
Early VLBI Experiments

- Motivation
  - High Brightness Temperatures
    - Variability
    - SSA (CTA21,CTA 102, 1934-63)
    - Interplanetary Scintillations
  - OH Masers – MIT/Harvard
  - GB-Md Point @ 50 cm
  - GB-Haystack @ 18 cm
- Crossing the Atlantic
  - GB - Haystack – Sweden (18 & 6 cm)
- US - Australia
- Penetrating the Iron Curtain
    - λ = 1.3 cm – 0.0002 arcsec



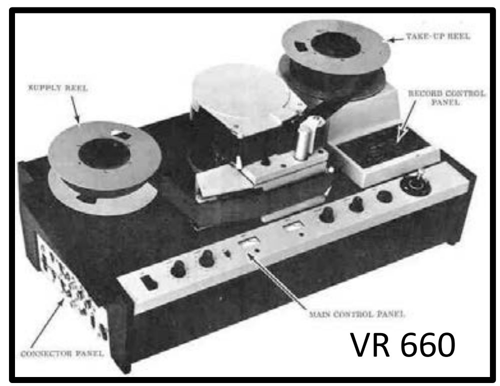


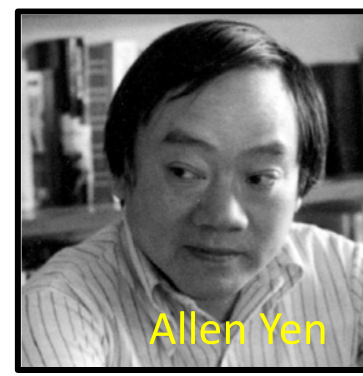
Slish, 1965
Williams, 1966



Early VLBI Instrumentation

- NRAO- Cornell MK I System
  - Computer Tape Drive
  - 1 bit sampling at 720 kbps
  - Software correlator IBM 360-50
    - 3 min recording/1 hour correlation
- Canadian System
  - 4 MHz analogue recording – TV recorder
- NRAO MK II – 4 Mbps
  - Hardware correlator
    - NRAO- 3 stations
    - Caltech 3, 4, 5, 16 stations
  - VR 660 (10 lb tapes)
  - VCR (Allen Yen) (>20 units)
    - 3 hour cassette $3
- MIT – Haystack MK III
  - 112 Mbps
  - 13 min (3 hrs)
  - $1000 per tape





Early (dis)organization

- It was exciting but hectic
  - 0.001 arcsec in less than a year
  - Travel to exotic places
  - Dealing with Russia
  - Dealing with referees
  - Violating physics? (Burke, 1969)
  - Superluminal motion – 1971

- But
  - Too few baselines – no phase information
  - Labor intensive
    - Bad recordings
    - Unlocked oscillators
    - X polarization
    - Timing errors (up to 1 sec)
    - ????
  - "Half an interferometer is like half a pair of scissors" – George Purcell

The Network Users Group

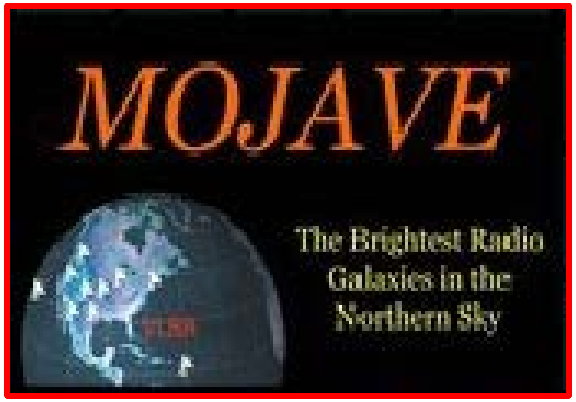
- 1975 - The US Network Users Group - NUG
  - 140-ft, OVRO, Ft. Davis, Haystack, Hat Creek, GB (Arecibo, Bonn)
  - 6 weeks/yr
  - Technical committee
    - Standard frequencies
    - Real time fringe checks
  - Handbook, newsletter
  - Bottom-up activity

- 1977 Real time satellite link NRAO – ARO (20 Mbps)
- 1981 US VLBI Consortium (Caltech, MIT, Univ. Cal, Iowa, IL, Harvard)
  - In absentia observing
  - Local telescope "friend"

VLBA

- 1984 -1993 VLBA construction
- 1994 VLBA Operations (HSA, Global)
- Key Projects
  - BeSSel
  - MCP
  - Pleiades
  - MOJAVE

VLBA, MOJAVE, and Relativistic Jets

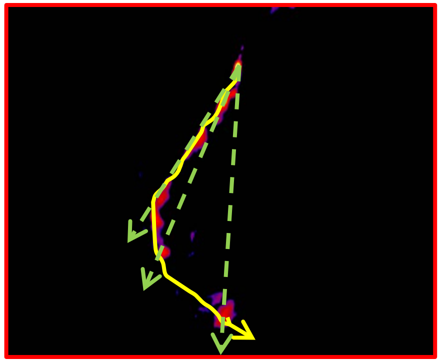


VLBA MOJAVE Members

M. Lister, J.T. Savolainen, J. Richards, D. Homan , J.A. Zensus Y. Kovalev M. Cohen, T. Hovatta A. Pushkarev E. Ros M. Kadler H. Aller, M. Aller, T. Arshakian, K. Kellermann

4968 MOJAVE + 2cm Survey images

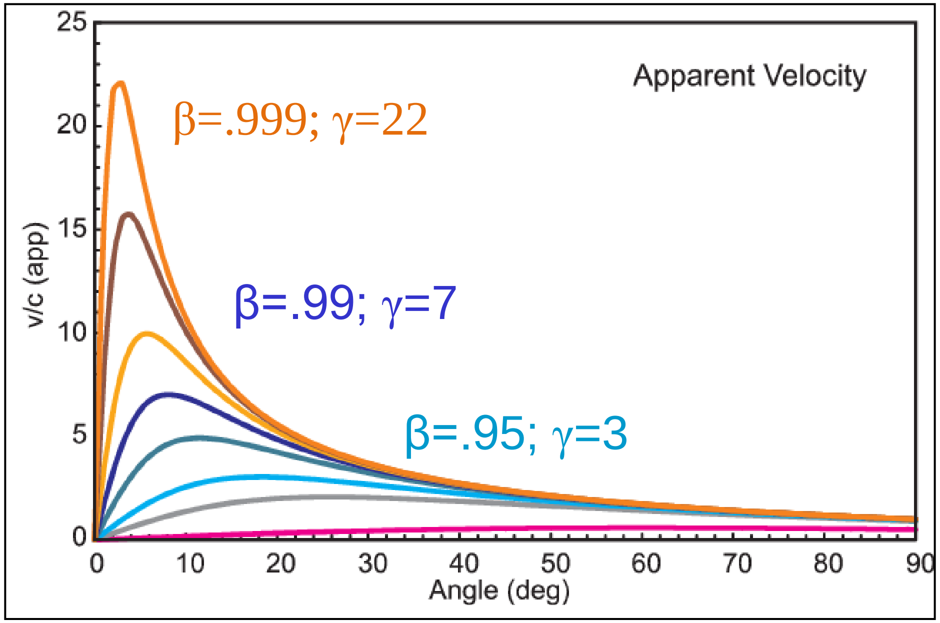
- Where and how is the relativistic beam accelerated and collimated
- Does the flow follow a curved trajectory or is motion ballistic?
- Does the apparent pattern velocity reflect the true bulk velocity?
- What is the maximum brightness temperature? Is there a limit?
- What is energy production mechanism
- What can we learn about the nature of the SMBH

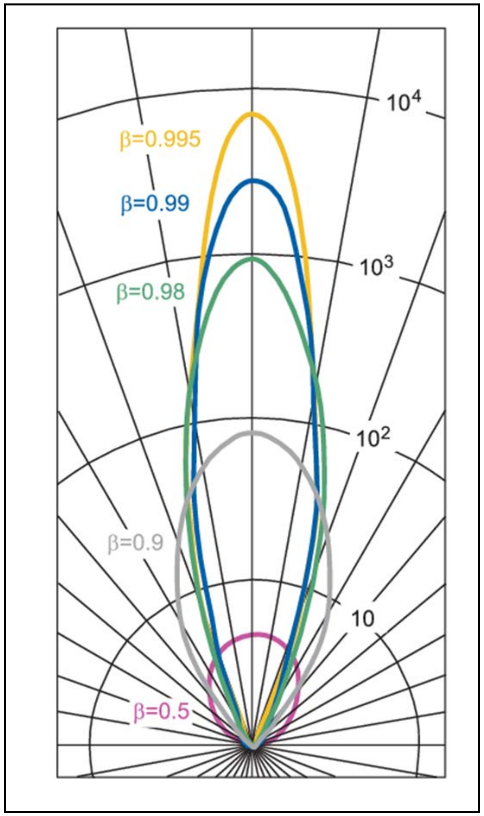


Relativistic Beaming in a nutshell

Doppler Factor: $\delta = \gamma^{-1}(1-\beta\cos\theta)^{-1}$

Lorentz Factor: $\gamma = (1 - \beta^2)^{-1/2}$; $\beta = v/c$





$\beta_{obs} = \beta\sin\theta/(1-\beta\cos\theta)$

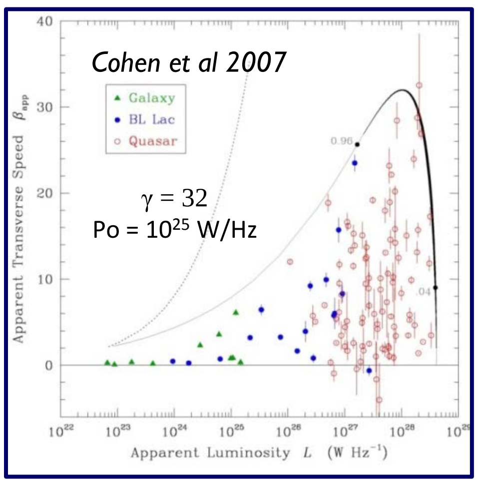
Sin $\theta \approx 1/\gamma$, $\beta_{max} \approx \gamma \approx \delta$

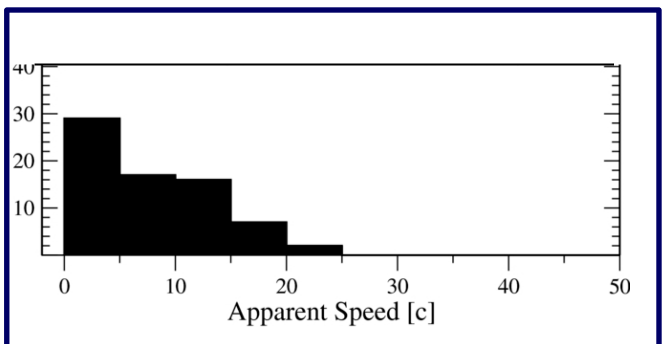
Assume $\beta_p = \beta_b$?

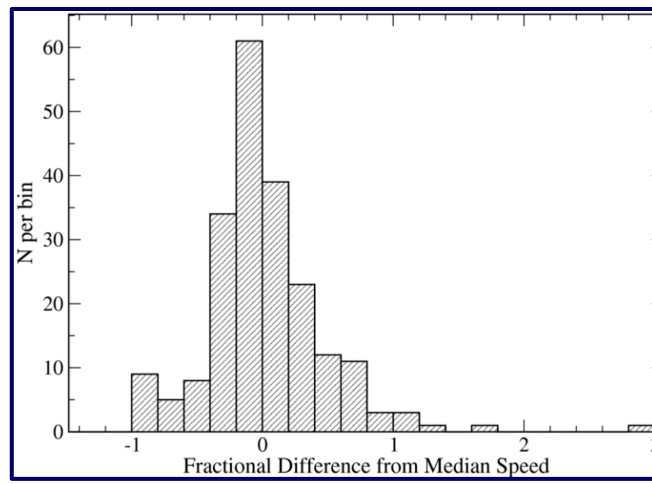
$S/S_0 = \delta^{x-\alpha} \sim \delta^{2-3}$

Parsec-scale jet kinematics

- One-sided jets – Doppler boosting/Edge Brightened
- Apparent speed distribution
  – Flux density limited sample (MOJAVE) $\beta_{typ} \sim \gamma \sim 8$
  – Randomly oriented mildly relativistic $1 < \gamma_{typ} < 2$
- Characteristic (bulk) jet speed
- Acceleration common (~ 70%)
  – Changes in speed more common than in direction
    - Change in Lorentz factor

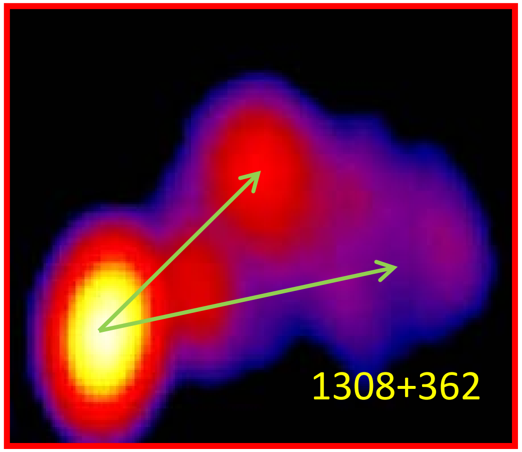


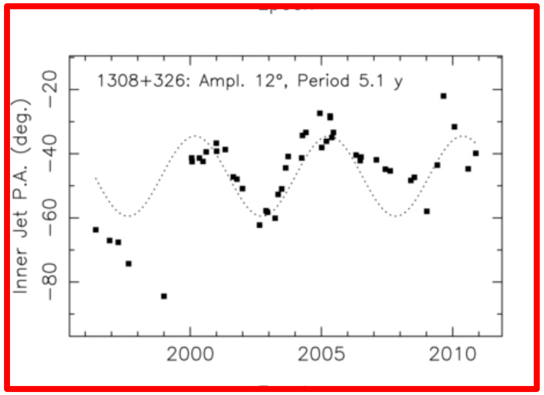




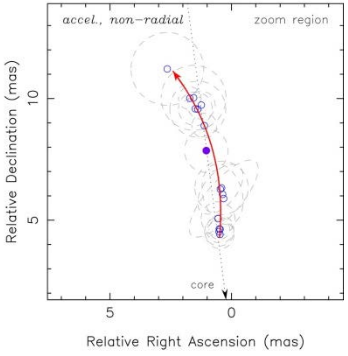
Jet curvature

Balistic motion – rotating nozzle?





Bending – preferred path



Brightness Temperature Theoretical Limits

Inverse Compton Cooling: $T = 10^{11.5}\ K$

(Kellermann and Pauliny-Toth,1969)

Equilibrium $(E_e \sim Em):\ T = 10^{10.5}\ K$

(Readhead 1994)

Brightness Temperature Observational limits

$$T_b = \frac{2\ln 2}{\pi k} S\lambda^2/\theta^2$$

$$\theta = \lambda/D$$

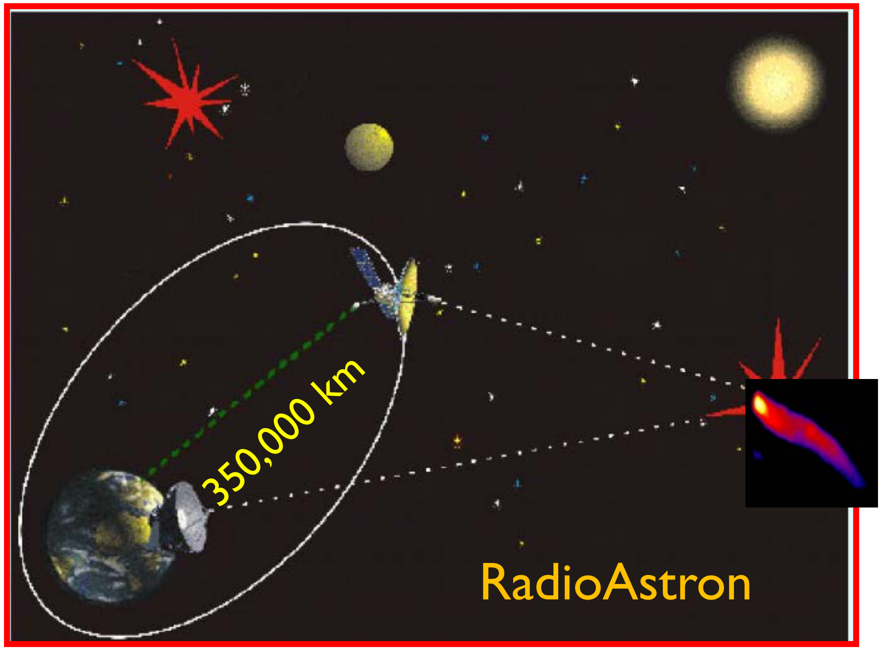
$$T_b \sim 80 S_{Jy}\, D_{km}^{\ 2} \left[\ln\left(\frac{S_{Jy}}{S_{Jy}-\sigma_{Jy}}\right)\right]^{-1}$$

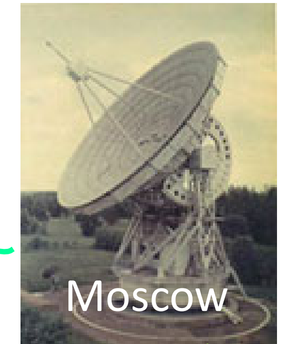
$S = 10 \pm 0.5$ Jy; D= 8,000 km

$T_b\ (max) \sim 10^{11}$ K

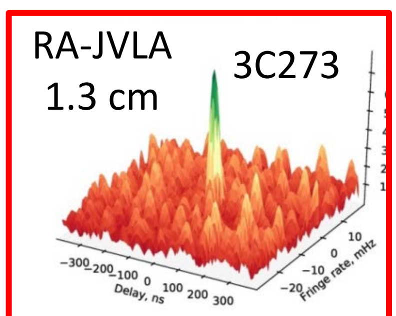

RadioAstron
Space VLBI Mission


July, 18
2011


350,000 km
RadioAstron



Bonn Moscow JIVE

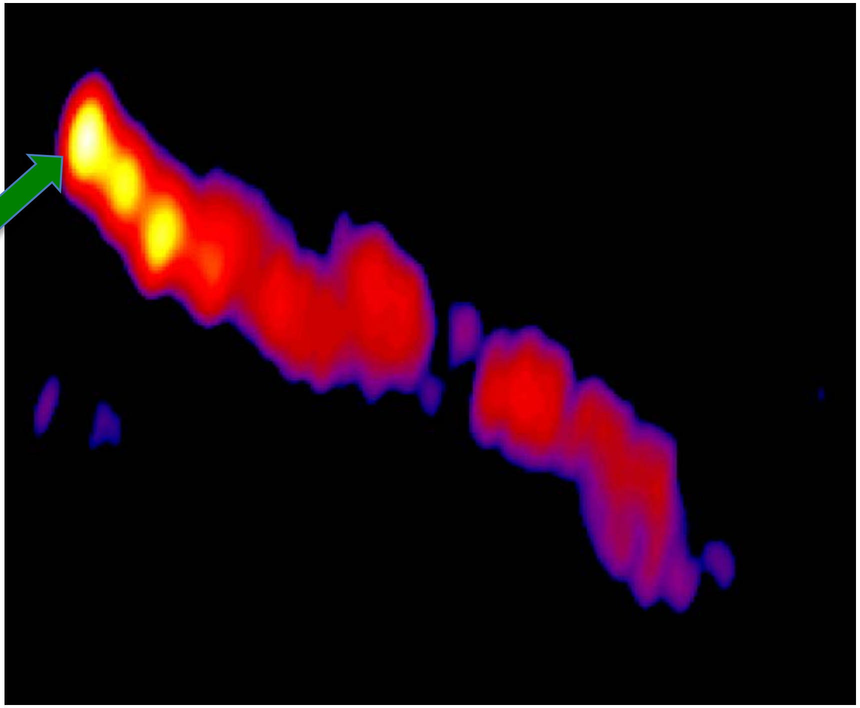


Measured 3C 273 Brightness Temperatures

$\theta \leq 3x10^{-5}$ arcsec

$T_b \geq 10^{14}$K

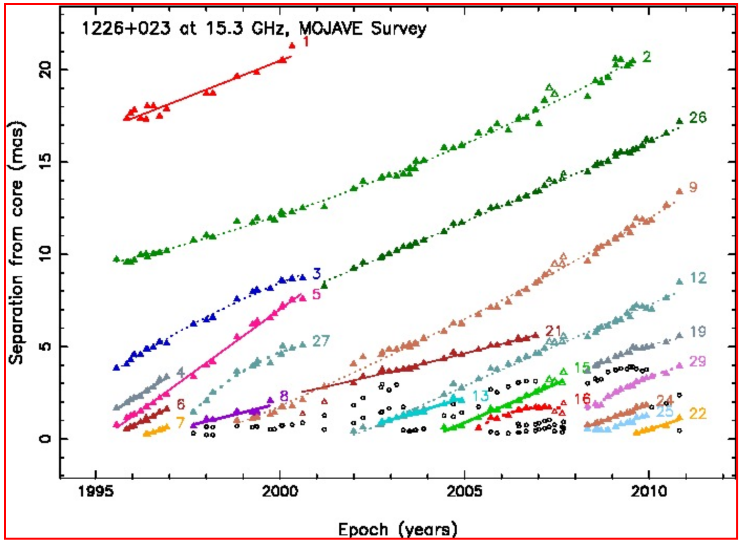
Kovalev et al. in prep.



Observed T_b ~ 10^2 to 10^3 greater than predicted

How can T_b reach 10^{14} K?

- Doppler boosting
  - $T_{obs} = \delta T_{int} \sim \gamma T_{int} \sim \beta_{app} T_{int}$
  - $\beta_{app} \sim 15$
  - $\nu_b >> \nu_p$?
- Continued particle acceleration
- Proton synchrotron radiation
  - $T_p/T_e = (m_p/m_e)^{9/7} \sim 10^4$
  - $B \propto (m_p/m_e)^2$
  - Electrons absorb
- Coherent emission
  - Pulsars
  - Sun
- Stimulated emission
  - Synchrotron maser
  - Cyclotron maser (Jupiter, stars)



Summary and Reflections

- Effective international collaboration
  - Needed for the science
  - Driven by scientists, not institutions or governments
    - 60 Hz NTSC TV standard
  - USSR and China participation organized at low levels
- VLBA Key Projects?
- Trust but verify
- Don't try to do it on the cheap
- Don't try to do too much
  - Too many snapshots
  - Not enough full track images
- Be realistic
  - 1965: No costly new facilities; only instruments on existing telescopes
  - 2015: VLBA, Space VLBI, JIVE - ERIC
- Fundamental physics (SMBHs) or interstellar weather?
- Most exciting result – $T_b >> 10^{12}$ K

Acknowledgements