Cm-wavelength VLBI Astrometry and mm-wavelength ALMA Astrometry

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Astrometric Projects Over the Decades

Caltech: ~1968: Quasar ID's and Structure

Early Identifications, double structure

NRAO: ~1975: 35 km-interferometry

Discovery of Sgr A*, Gravitational bending to 1%

Reference Frame: 1970-now: Global VLBI

Define ICRF, plate tectonics, earth orientation

VLBA, EVN, Vera: 1990-now: Dynamics

Distance, galactic structure, maser-based H_0

Multi-Wavelength: ADeLA-2014 talks over few days.

TOPICS IN THIS TALK

Examples of cm-wave Astrometry:

- ICRF and quasar changes
- Measurement of speed of gravity
- Evolution of Sco X-1 radio emission (micro-quasar)

ALMA mm-wave Astrometry:

- Distance to Pluto for New Horizons Mission
- Progress of ALMA Long-Baseline Campaign
- Future ALMA astrometric Projects

Radio-defined Inertial Frame

Quasars as Celestial Beacon

- Cosmological distance
- Compact component
- Radio arrays over 1000 km can be coherently connected
- Radio emission bright for accurate celestial position

VLBI Experiments of quasars since 1970 :

- Obtain quasar positions and stability
- Determine Earth rotation/orientation in space
- Find Terrestrial Frame (GPS and laser ranging) of antennas

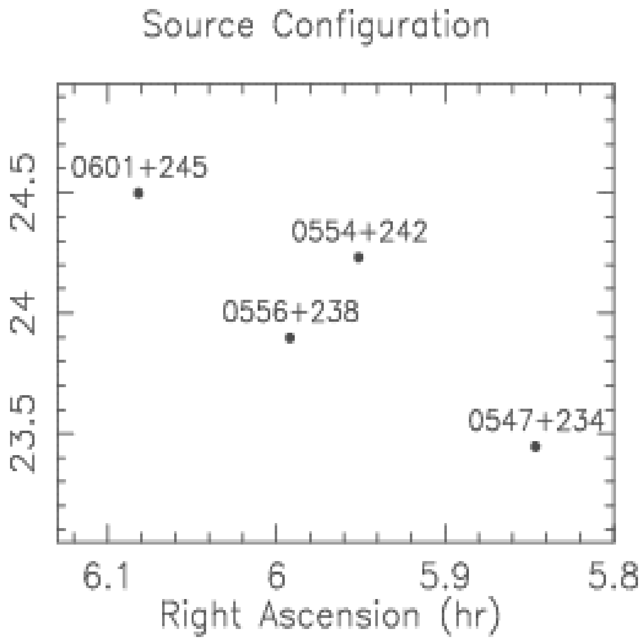
Current International Celestial Reference Frame

- Defined by position of ~200 high quality quasar positions
- Frame origin is solar system barycenter (not quite inertial)
- Orientation accuracy about 10 microarcsec

HOW STABLE ARE QUASARS???

Quasar position at 15-500 μarcsec level

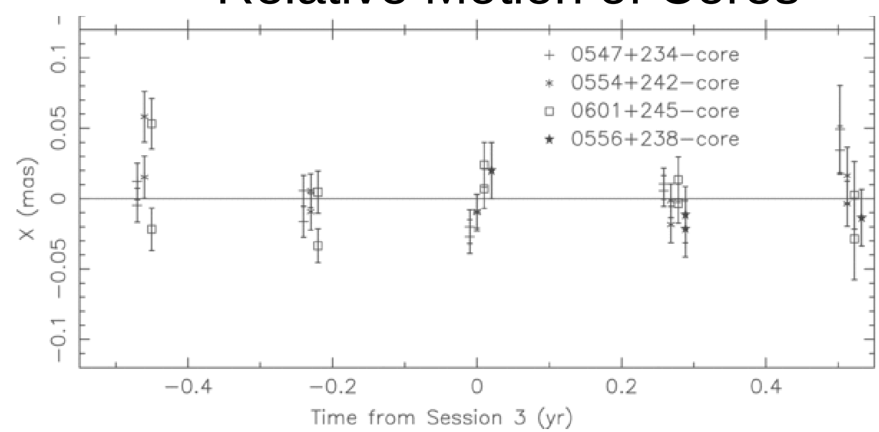
With K Johnston (USNO), M Honma (Vera, Japan)

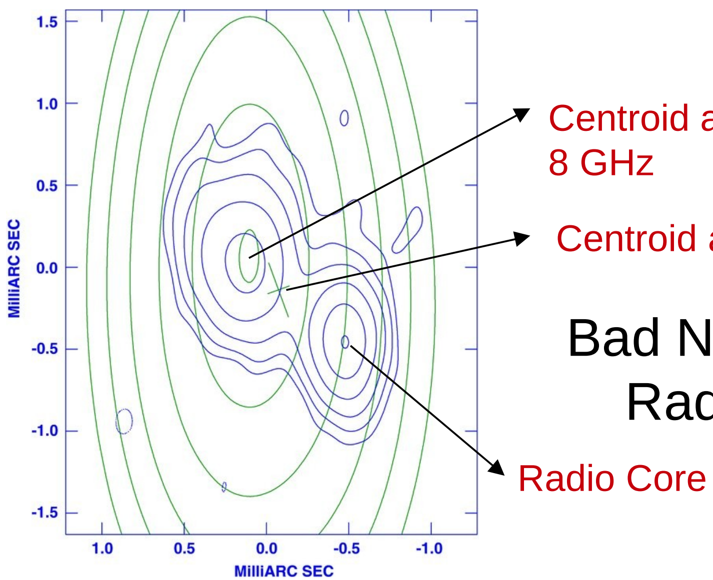


Phase reference among 4 ICRF2 sources

Using VLBA 15,23,43GHz, VERA at 23 GHz

Relative Motion of Cores





Good News: Core stationary to 15 μarcsec/year

Bad News: What is measured position of the Radio source?

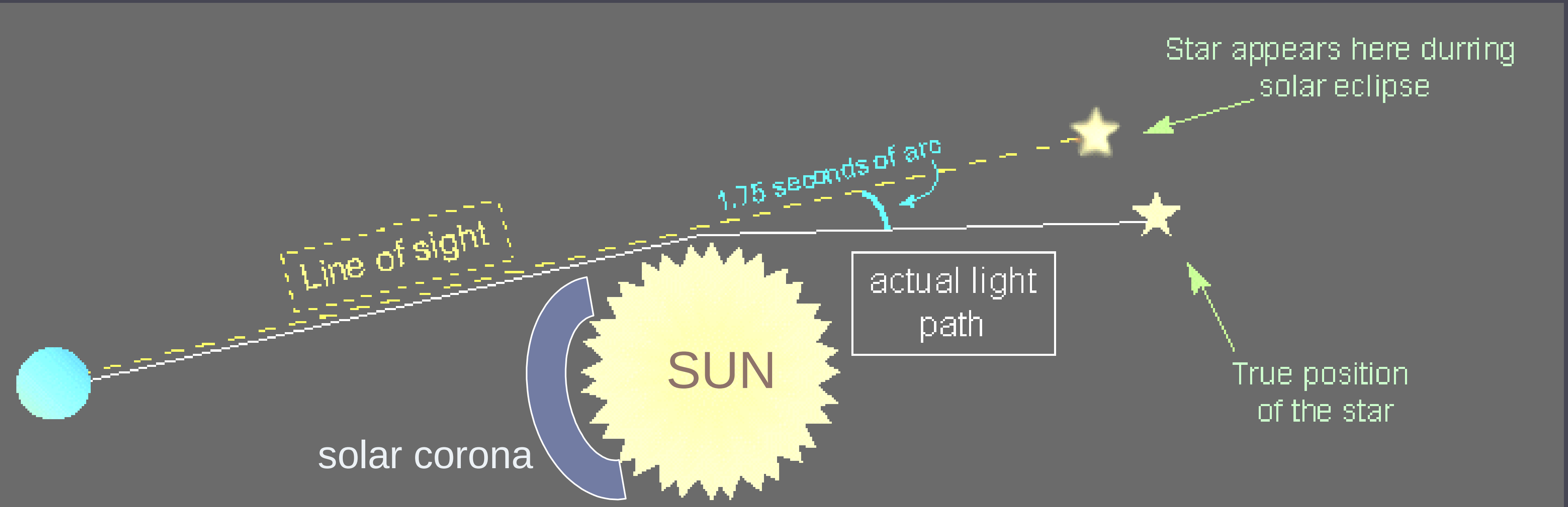
Test of General Relativity

Many optical/radio tests of GR.
Bending of light
Gravitational redshift
Pulsar dynamics

The most controversial was done in 2002 with
VLBA + Effelsberg antenna
The gravitational bending of light passed Jupiter
S. Kopeikin (U Mo), G. Lanyi (JPL)

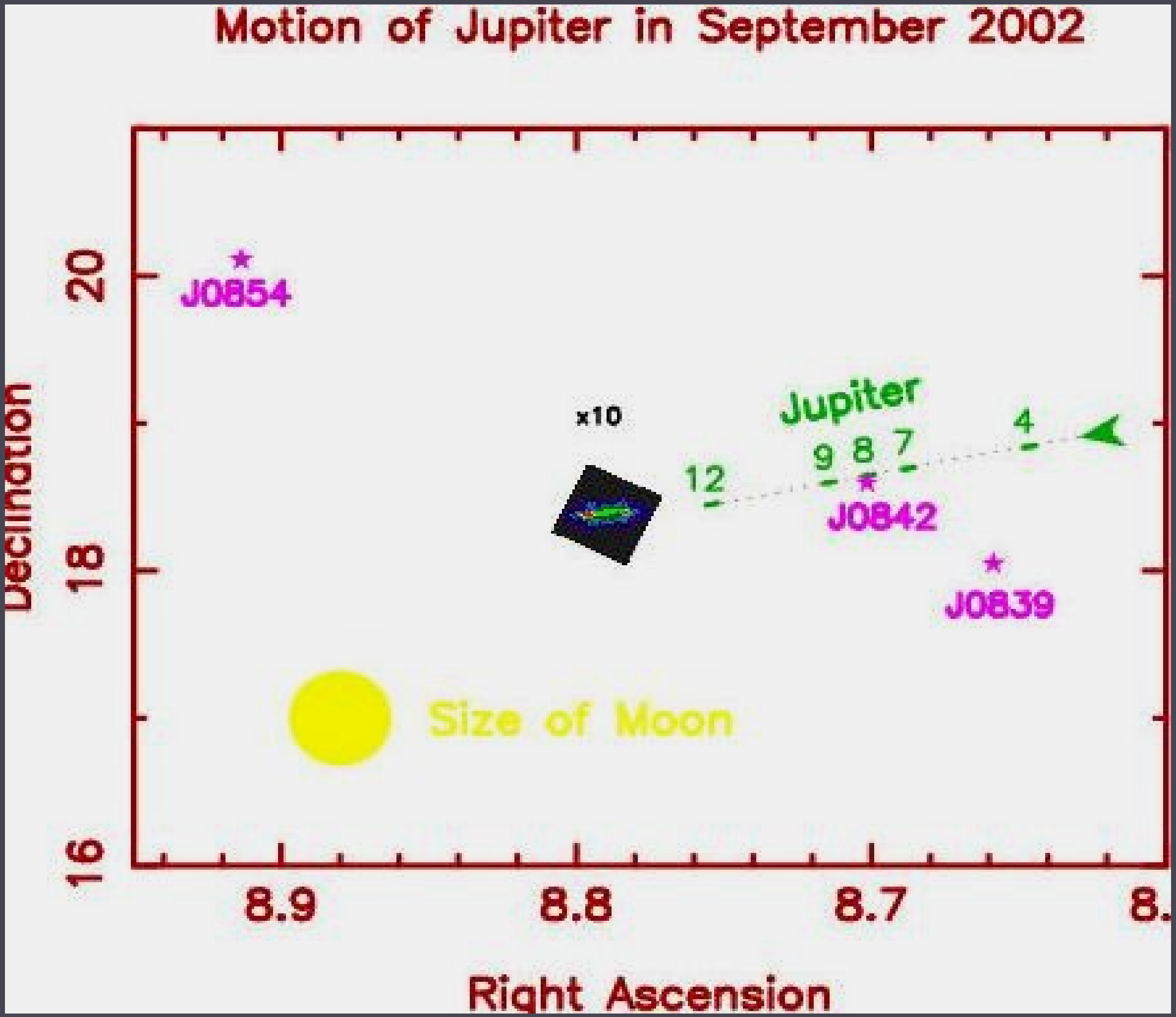
Gravitational Bending of Light (Radio) Waves

Measures the parameter gamma, the space curvature associated with unit mass for most plausible theories of gravity.
For General Relativity $\gamma = 1$ (normalized to semi-classical convention)
For Newtonian gravity $\gamma = 0.5$
For non-Einstein theories of gravity $\gamma < 1$ (1 part in 10^{-5} expected?)
Simple experiment using sun (1919, 1963, many radio exp after 1972)
A solar limb, bending is 1.76", radially away from the sun.



If moving planet instead of sun, more information

VLBA/Eff. Phase Reference Experiment



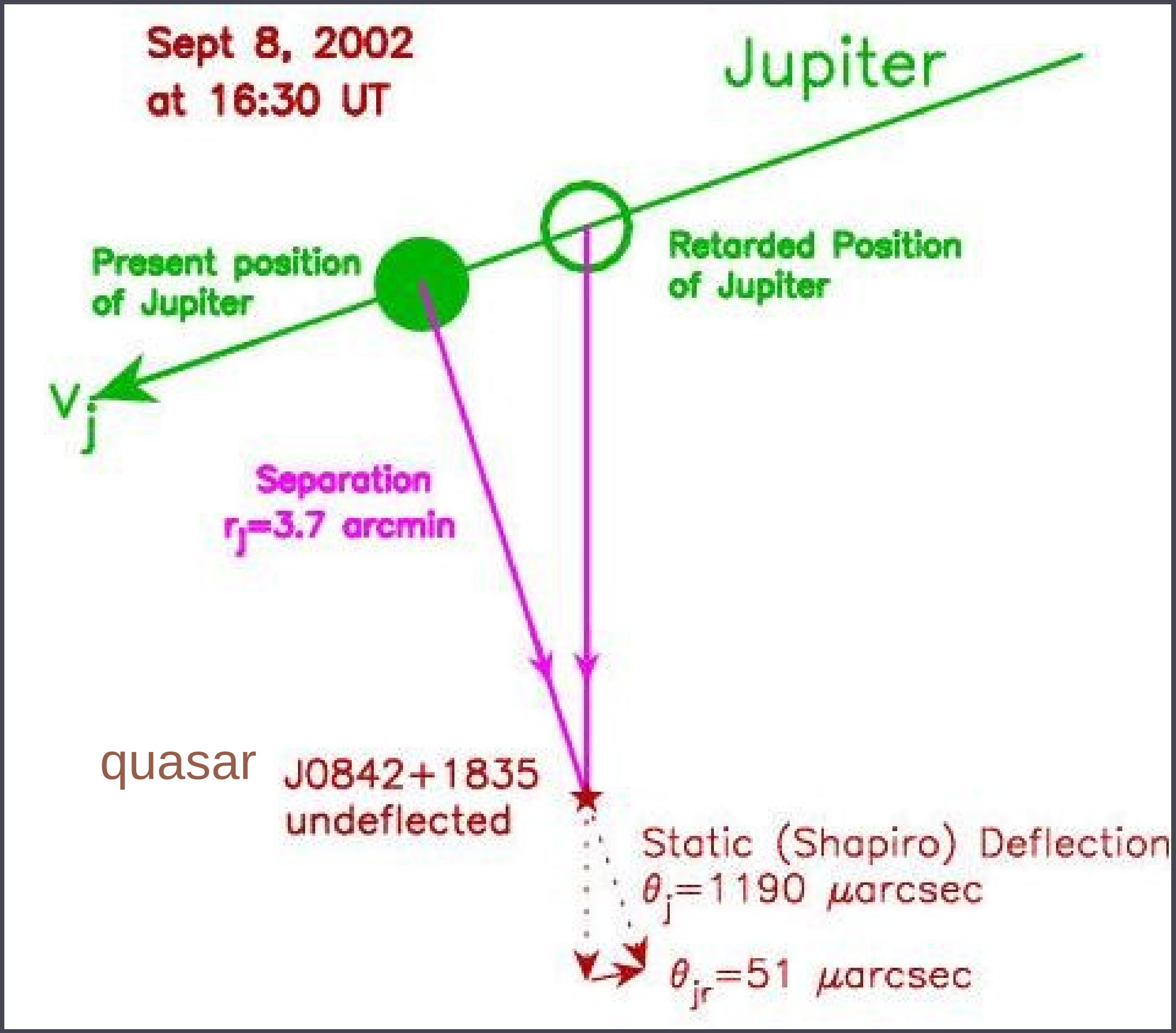
Phase ref means we cycle quickly among all of the sources and measure their angular separations every ten minutes

Observe at 8.4 GHz, Jovian Magnetosphere problem?

Use two sources on either side to remove atmospheric refraction since these source positions should not change. This removes the radio 'twinkling' with time-scales of minutes.

Measure position change of J0842 on Sept 8 with Respect to Sep 4,7,9,12

Gravitation Deflection from a Moving Object



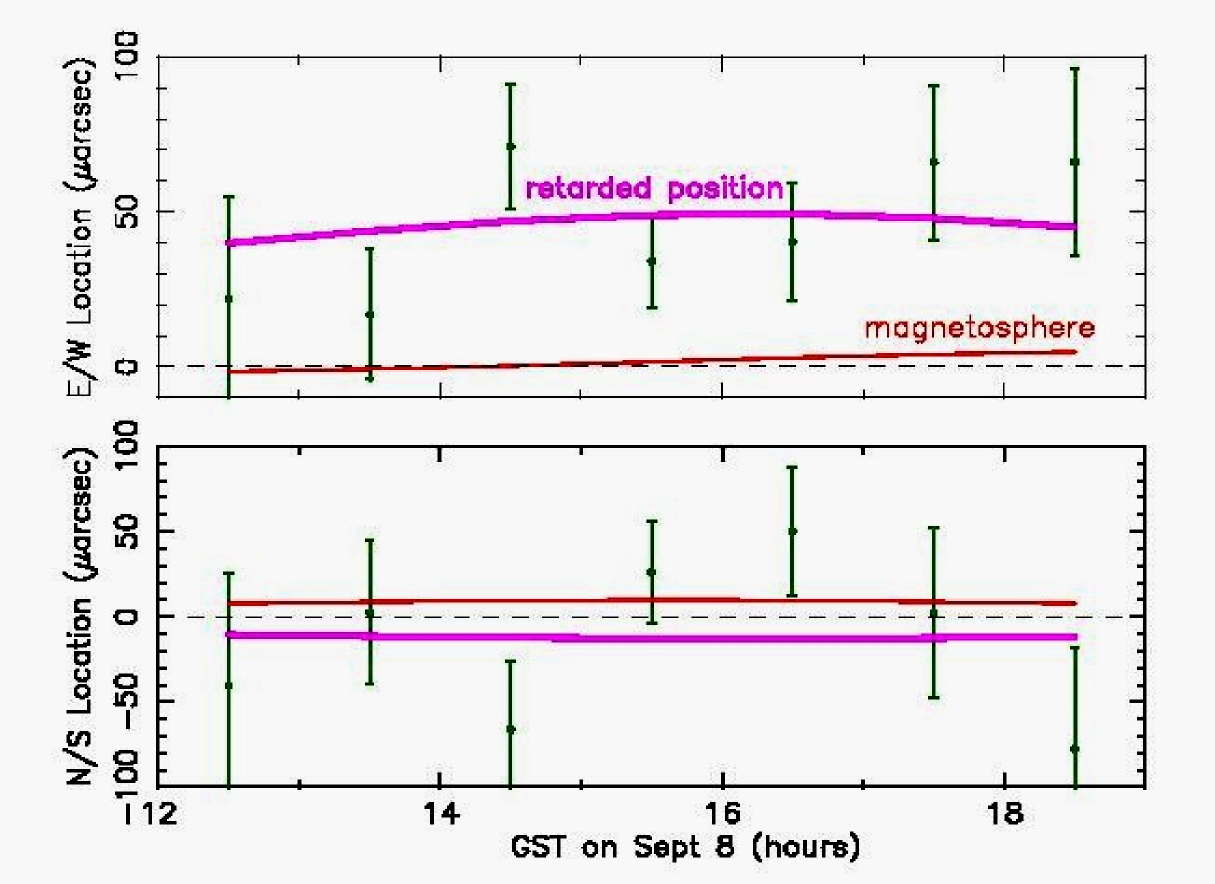
Unusual occurrence
Once every ~20 years

Deflection not precisely radial

1997 Kopeikin worked out deflections and planned to obtain telescope time with the help of someone who knew interferometry

The aberration term due to Jupiter's motion was 51 μarcsec assuming the gravitational effect propogating with c_g

Experimental Results



Plotted points give position of J0842 measured every hour on Sept 8, 2002 (Radial deflection of 1190 μas was removed)

Magnetosphere shift from Jupiter estimated from Galileo space craft.

θ_{jp} = (50 +/- 10 μarcsec = 0.98 +/- 0.19 times GR prediction

Since this displacement component is proportional to Jupiter's motion (known) and the speed of gravity, we obtain

$$c_g = 0.98 \pm 0.19\ c$$

Many Interpretations of the Experiment

- Will (2002) – Measured PPN parameter α_1. See http://wugrav.wustl.edu/people/CMW/speedofGravity.html

- Asada (2002) – This experiment measured the speed of light from the quasar to 20% accuracy.

- Samuels (2003) – Nothing of significance. Experiment did not measure any useful physical quantity, except that the Gravitationall field of Jupiter is attached to Jupiter.)

- Carlip (2004) – An undefined mixture of the speed of light and gravity depending on the particular parameterization of the Maxwell-Einstein equations.

Main difference of interpretation.

In the deflection experiment, the speed of gravity (v_g) enters as

$v_g \sim v_{jup}/c$ and higher orders (Kopeikin) ~ 50 μarcsec effect

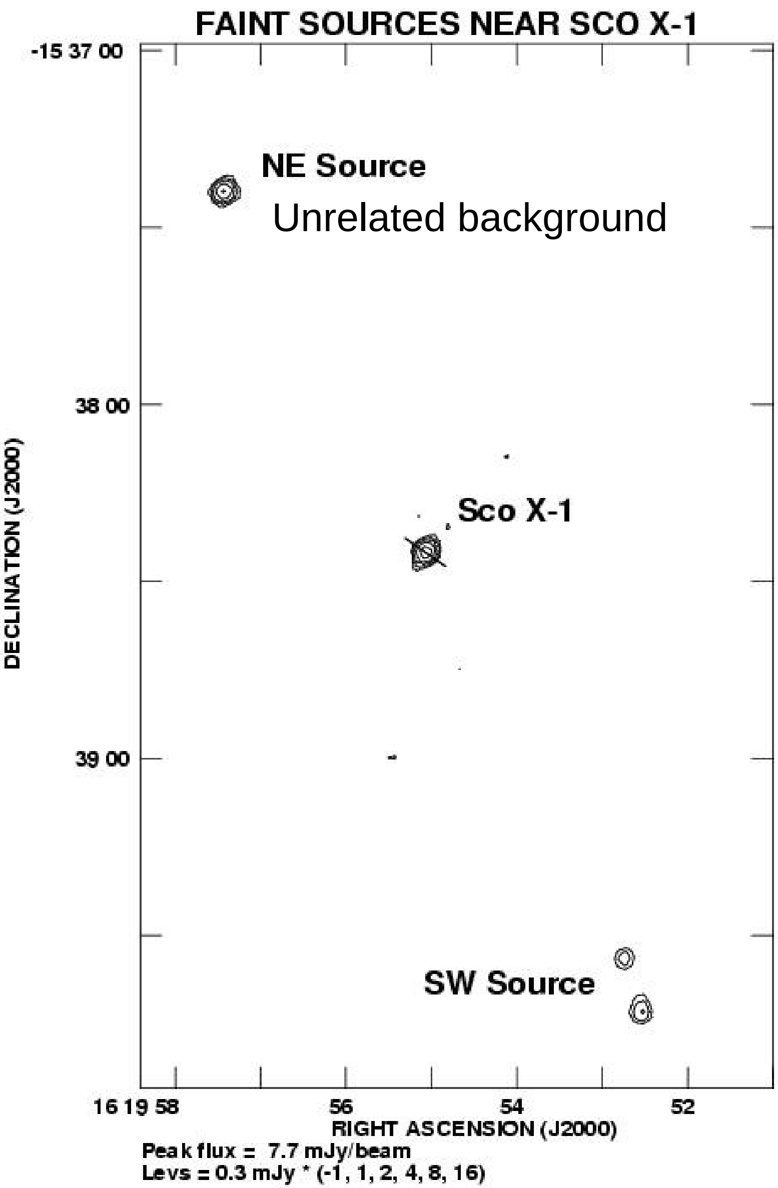
$v_g \sim (v_{jup}/c)^2$ (other interpretations) ~ 1000 times smaller!

The Evolution of Sco X-1

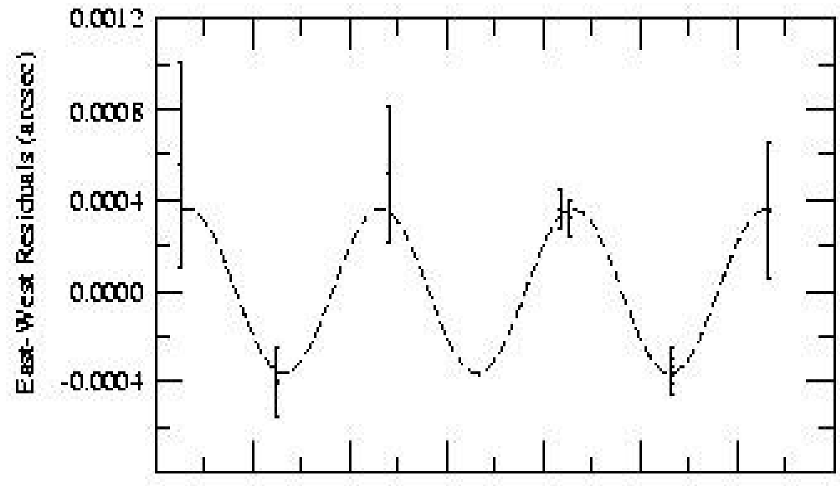
The brightest X-ray source in the sky
Evolves like a quasars, but much faster

A 56-hour continuous VLBI experiment was made

1990 VLA Image



1999 VLBA Parallax

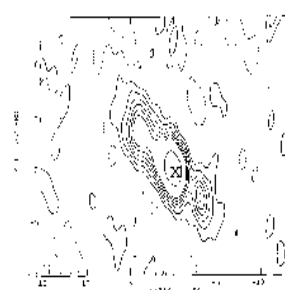


Sco X-1 is a variable radio source

1 mJy → 100 mJy

Parallax gives 2.8 +/- 0.3 kpc

Motion 1.1 mas/yr to south.



1999 VLBA Structure

Motion of lobes seen

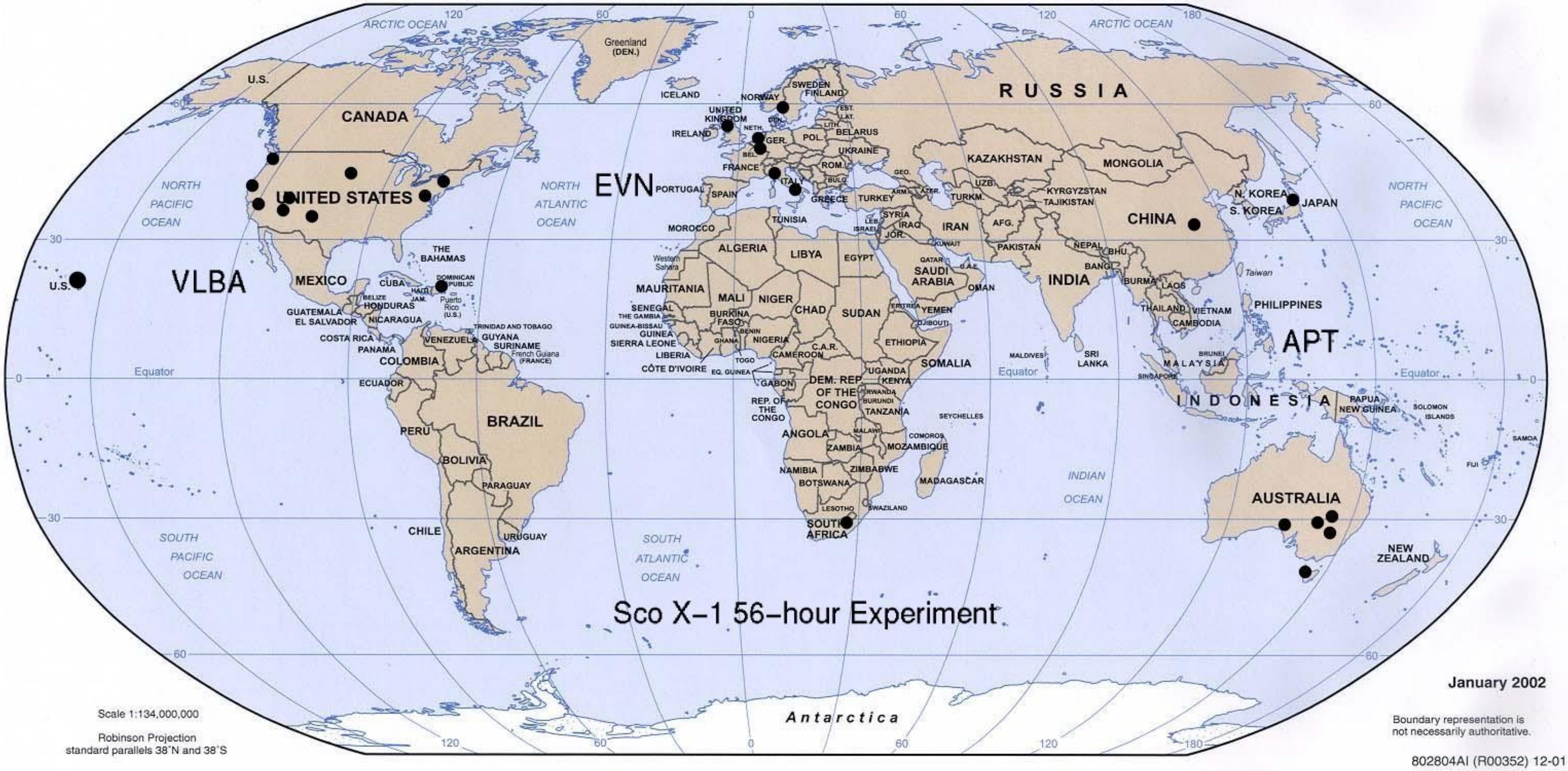
1 – 3 components

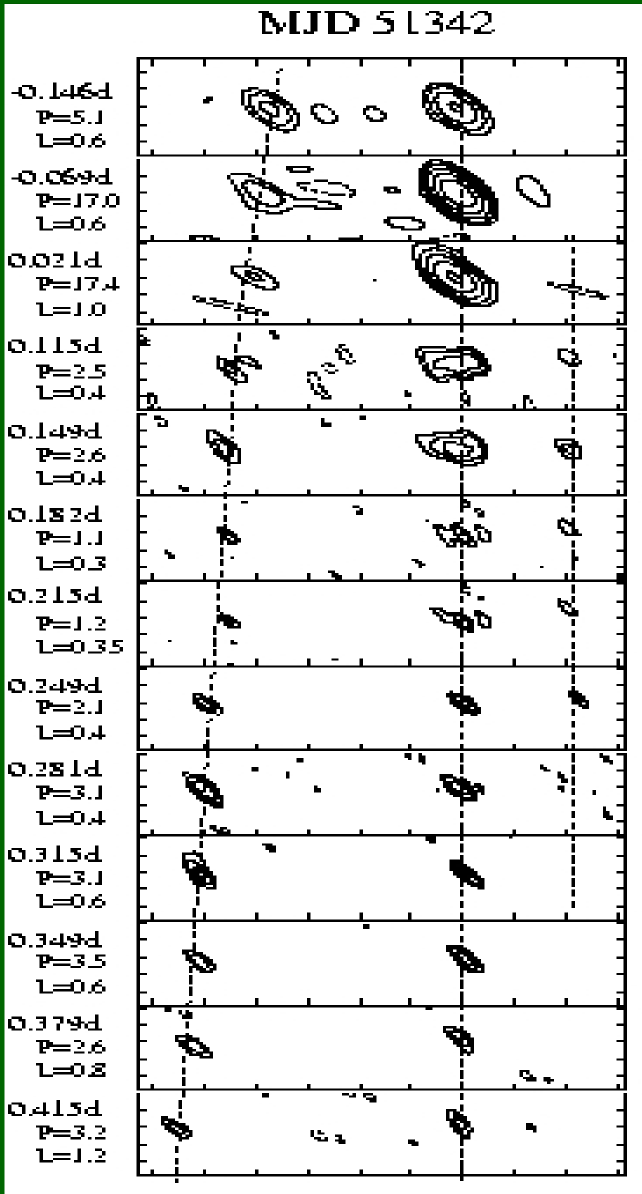
Continuous 56-hour VLBI observations of Sco X-1

June 11-13, 1999.   8 hrs each array

VLBA—APT—EVN—VLBA—APT—EVN—VLBA

Sco X-1 images made every hour





50 0 mas

NE lobe Core SW lobe

Sco X-1 Imaging over 56 hours

Images made every ~1 hour

5 GHz, 3 mas resolution & 1.6 GHz

Contour levels = 0.5 mJy

Position angle in sky = 54 +/- 1 deg

General Evolution

Radio emission on Sco X-1

NE lobe bright (left), moving away

SW lobe faint (right), some motion

All components variable

Basic asymmetry the same

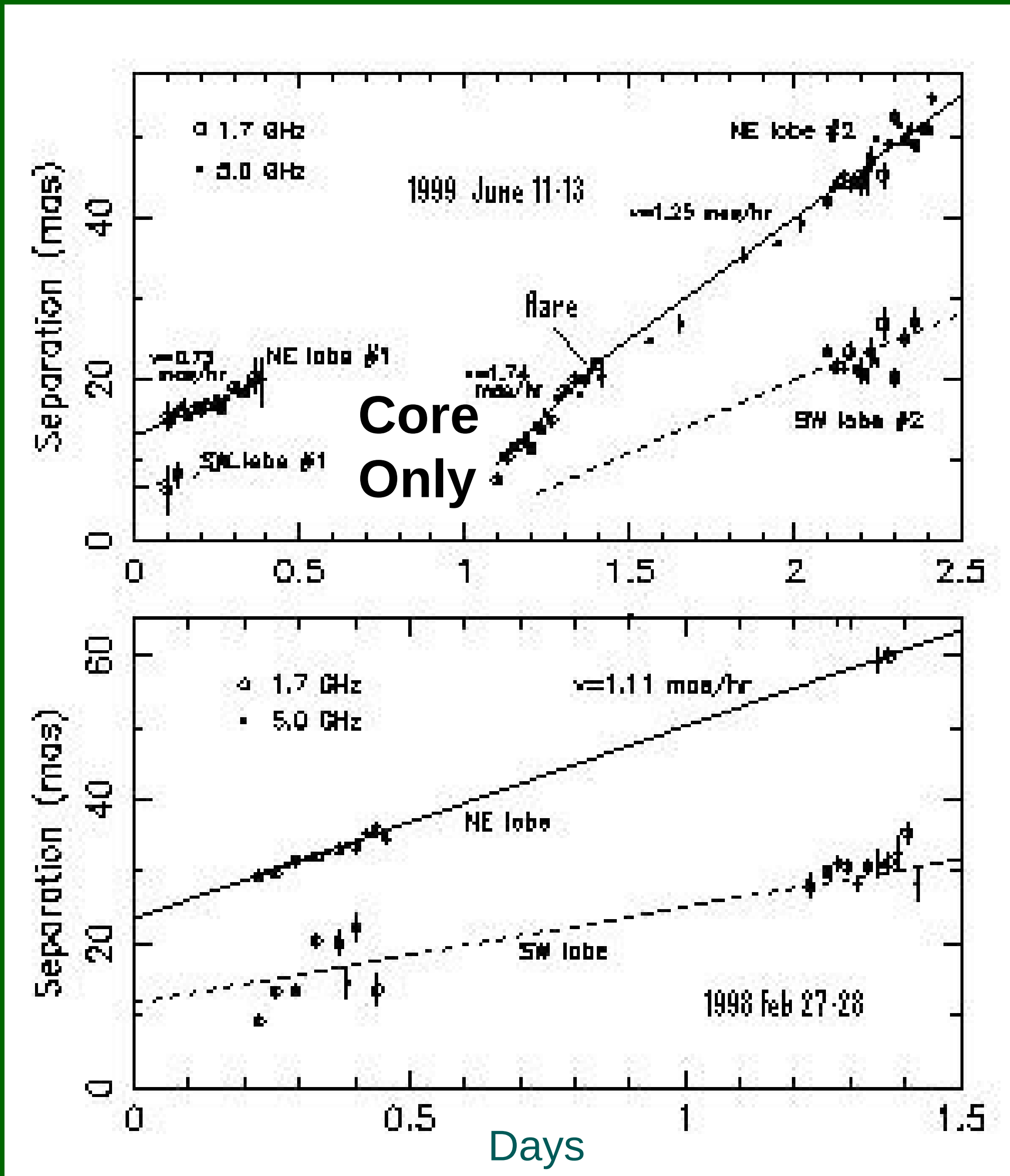
NE brighter then SW

NE moves faster than SW

10 mas = 28 AU = 4.2 x 10^{14} cm

1 mas/hr = 0.39 c (at 2.8 kpc)

MOTION OF LOBES AWAY FROM CORE



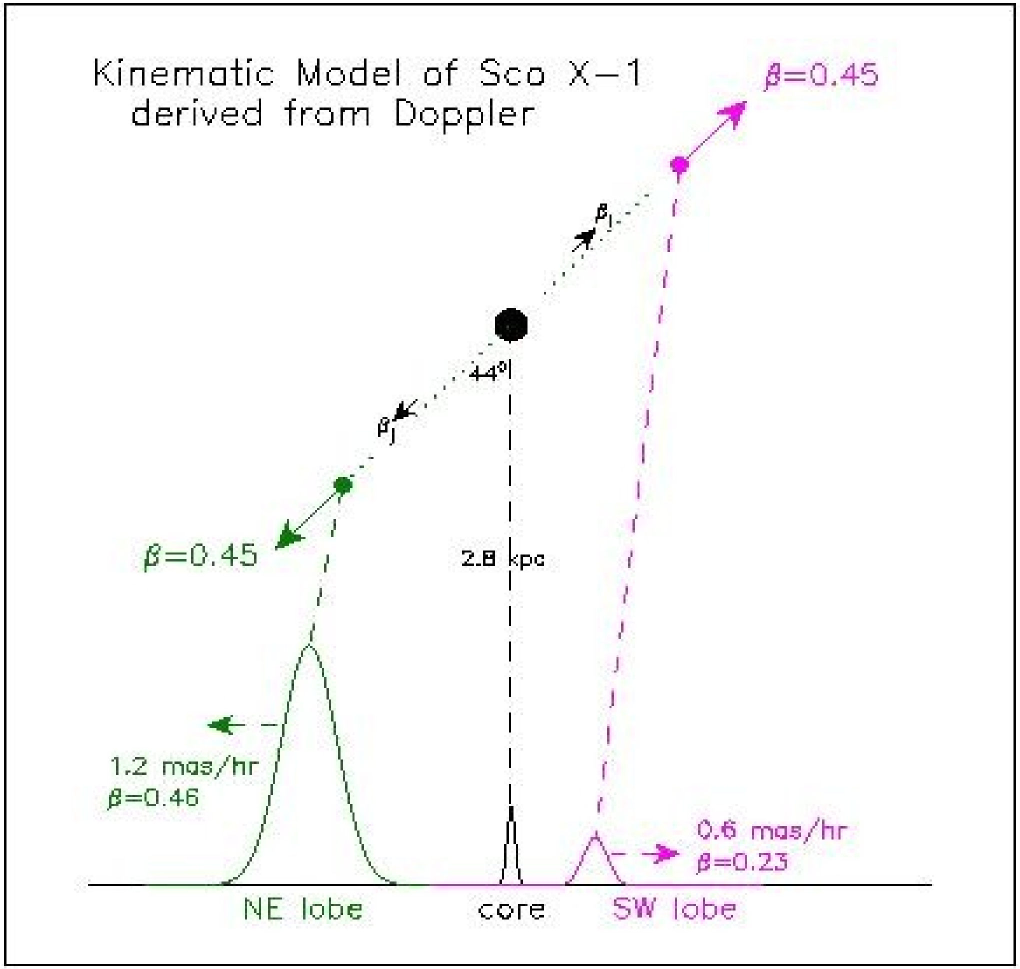
Lobe lifetime about 1-2 days
- Motion directly away from core
- Relatively uniform motion

NE lobe brighter than SW lobe
NE lobe moves 2 time faster than SW lobe

Top frame from 56-hour run

Bottom from two 8-hr runs
One year earlier.

Simple Kinematic Model



--Assume Source emission and motion is symmetric in its rest frame

--Knowing distance, convert to Intrinsic motiion

$\beta_{NE} = \beta \sin(\phi)/[1-\beta\cos(\phi)]$

$\beta_{SW} = \beta \sin(\phi)/[1+\beta\cos(\phi)])]$

$\beta = 0.45$ +/- 0 .03 (0.54)

$\phi = 44$ +-6 deg

β = speed of lobe advance?

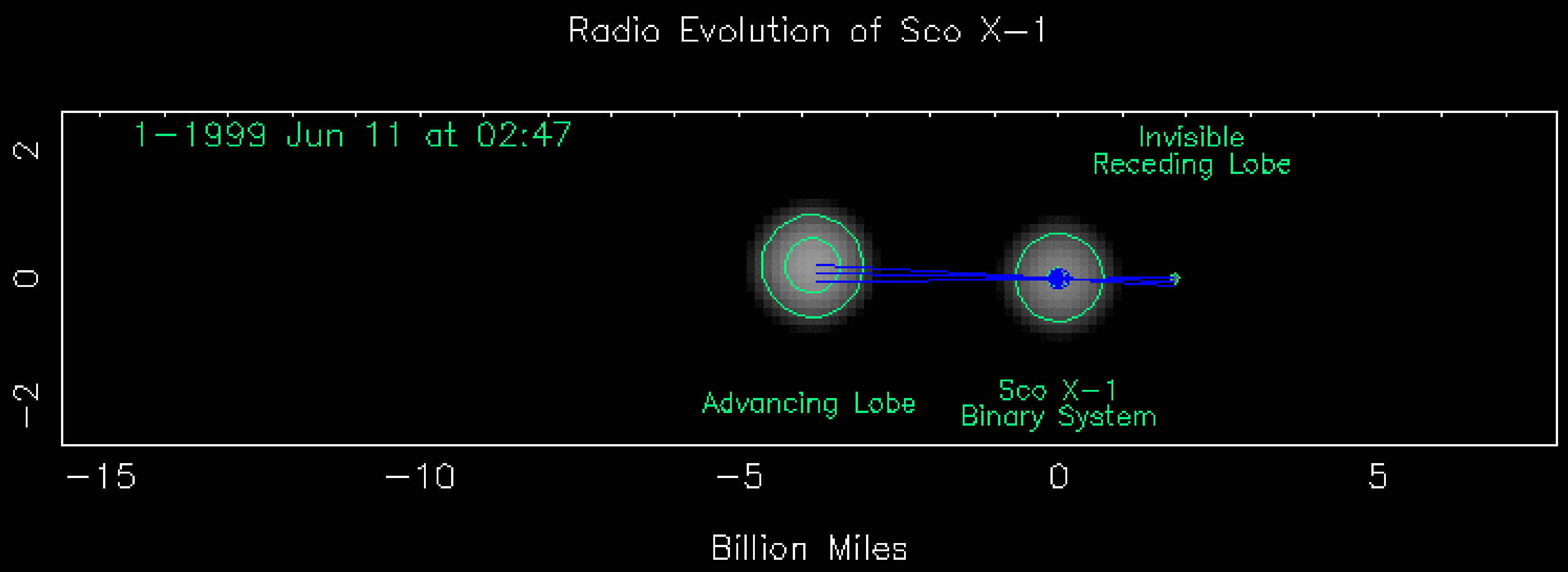
What about speed of jet flow?

β_J How to determine this

If core flares and increases energy flow to lobes, when will the lobes flare? Depends on β_J

Sco X-1 Movie

Emission shown by contours and grey-scale
Jets in blue (unobserved)
Binary location is blue dot
Proposed flare packets in white



EVOLUTIONARY Sco X-1 PROPERTIES

- All asymmetries of NE and SW lobe explained by Doppler effects.
  Symmetric flow of energy to both sides
  Jet interaction with external medium similar.
- Lobe space motion is ~0.4c, and is relatively constant.
  What is limiting this velocity
- Lobe flares consistent with core flares sending energy down jet with jet flow speed 1.00 c +/- 0.05 c
  (rule out protons?)
- When the energy supply stops (core becomes faint) , the lobe expands adiabatically and dissipates in about two hours.
- Scaling times vary as compact object mass, 10^6
  Time scale of **one day in Sco X-1 -> 30,000 yr in quasar**

Fomalont et al 2001, ApJ L, 553, L27
2001, ApJ, 558, 293

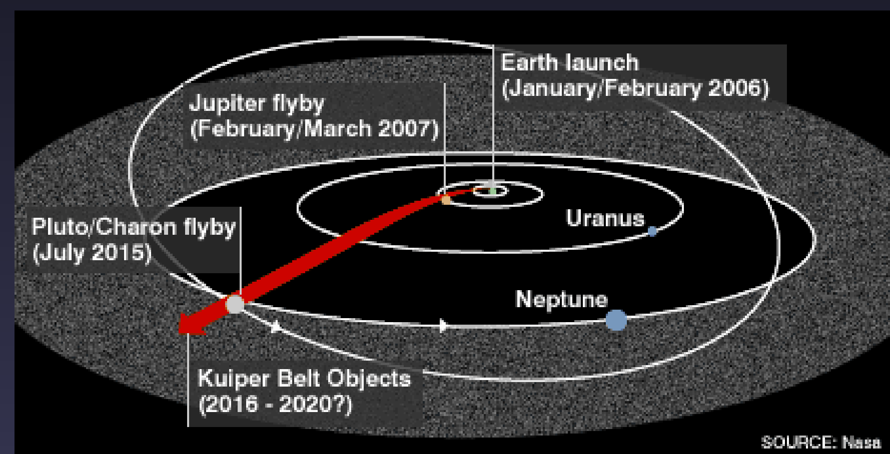
ALMA Astrometry

The First ALMA Astrometry Experiment

The Current Long-Baseline Campaign:

Some Future ALMA Astrometric Experiments

New Horizon Mission to Pluto and Beyond



Additional phase terms: $2\pi\nu(\tau^{tr}_1-\tau^{tr}_2)+2\pi/\nu(\tau^{IO}_1-\tau^{IO}_2)$

Why Measure the Distance to Pluto?

With A Stern and L Young (SwRI), H Weaver JHU), W Folkner (JPL)

Time of arrival critical to many measurements:

- **Previous uncertainty of~5000 km leads to 3 hr arrival uncertainty of**
  - **When to turn on cameras and pointing?**
  - **Can find Pluto with Camera 5 days before arrival**
  - **Course correction risky and expensive in fuel and needed**
  - **Need extra fuel for possible post-Pluto encounters**

Radio astrometric will tie Pluto optical obs to ICRF frame

- **Compare with many optical/Hubble obs**

Course correction on July 15

- **Based on ALMA three epoch obs+ optical reanalysis**
- **Present uncertainty of~2000 km**

Two signals add in phase

Another Course correction around Jan 1

Additional phase terms: $2\pi\nu(\tau^{tr}_1-\tau^{tr}_2)+2\pi/\nu(\tau^{lo}_1-\tau^{lo}_2)$

WHY ALMA OBSERVATIONS OF PLUTO

Pluto faint thermal object:

- 25 mJy at 350 GHz, 0.03 mJy at 43 GHz
- 40 min ALMA experiment, 20 hr VLA experiment

Angular sizes:

- Pluto is 0.08” in size. Pluto-Charon sep is 0.7”
- VLBI too much resolution

ALMA at 350 GHz with 0.5 to 1.5 km baseline optimum

Parallax Measurement Standard for VLBI

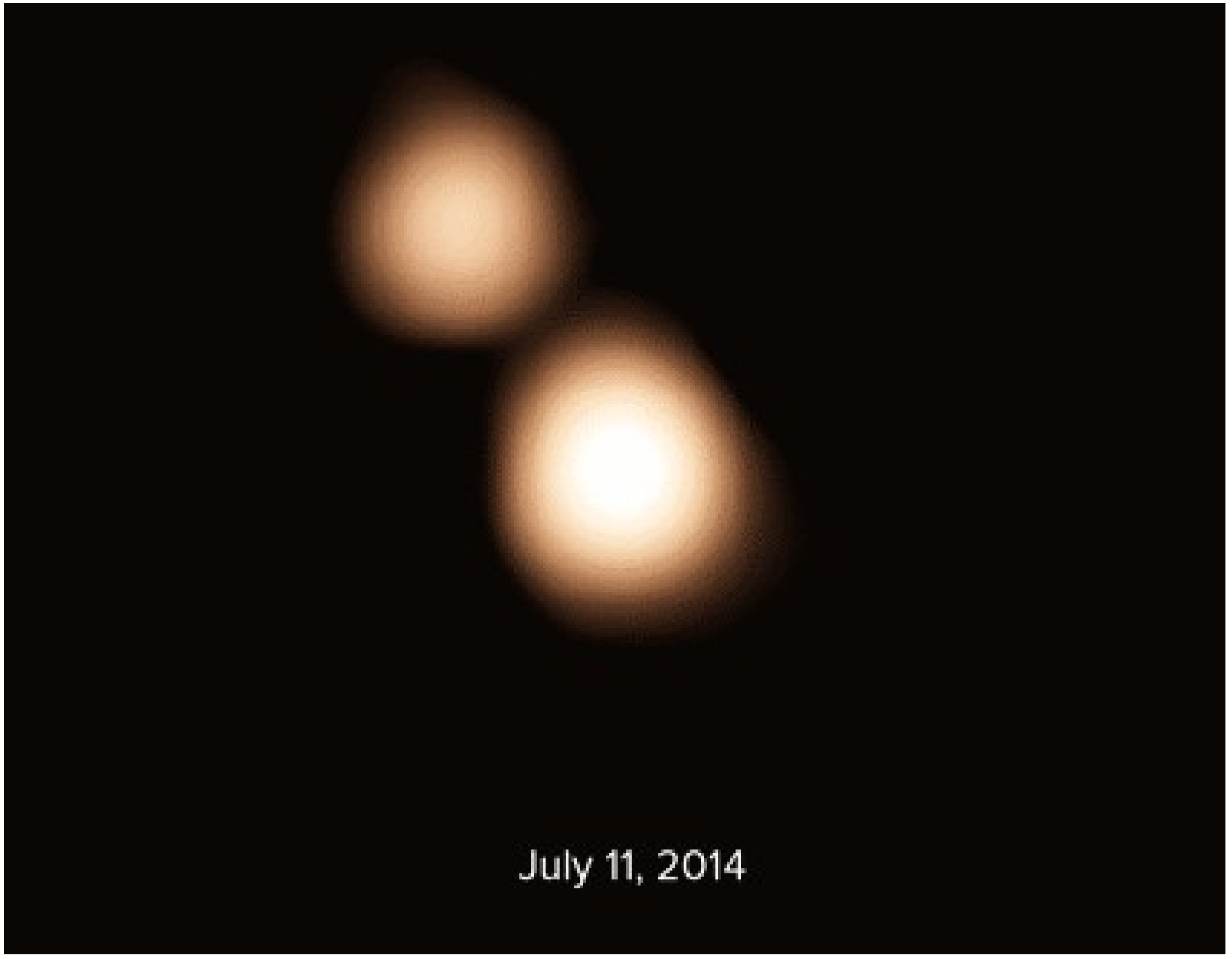
- Nov 2013, April 2014 (2), July 2014(2)
- Observation panned in Nov 2014

Accuracy Obtained (compared with optical data)

Two signals add in phase

- RA~0.005”,   DEC~0.013” (we know why now?)

Additional phase terms: $2\pi\nu(\tau^{tr}_1-\tau^{tr}_2)+2\pi/\nu(\tau^{io}_1-\tau^{io}_2)$


July 11, 2014

ALMA: current status

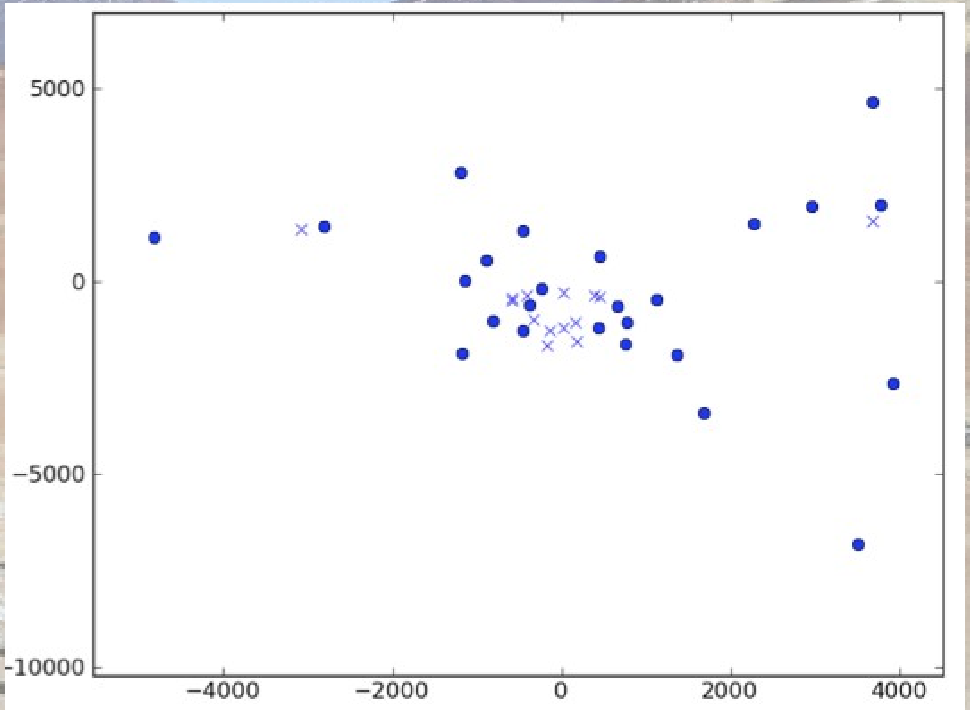
- Atacama Large Millimeter/submillimeter Array - located in the Atacama desert (Chajnantor plateau) in northern Chile (~5100 m). Operations led by ESO, NRAO and NAOJ.
- Inaugurated March 2013
- All 66 ALMA antennas now delivered
- 54 12-m antennas and 12 7-m antennas (ALMA Compact Array – Morita Array)
- 63 antennas currently at Array Operations Site: 51 12-m antennas, and 12 7-m antennas

Overview

- ALMA Long Baseline Campaign will take place from:
- 1 September - 30 November 2014
- Ed Fomalont (*Campaign/Techncial Lead*)
- Catherine Vlahakis (*EOC management & Science Verification Lead*)
- Campaign run and organized by JAO/EOC with support from personnel from the ARCs and ARC nodes (both in Chile and remotely)
- During the campaign there will be only EOC (CSV) time, **no Early Science observing**
- Long Baseline work will take highest priority, but some other EOC activities will also be carried out (e.g. testing of new software version)

Long Baseline Configuration

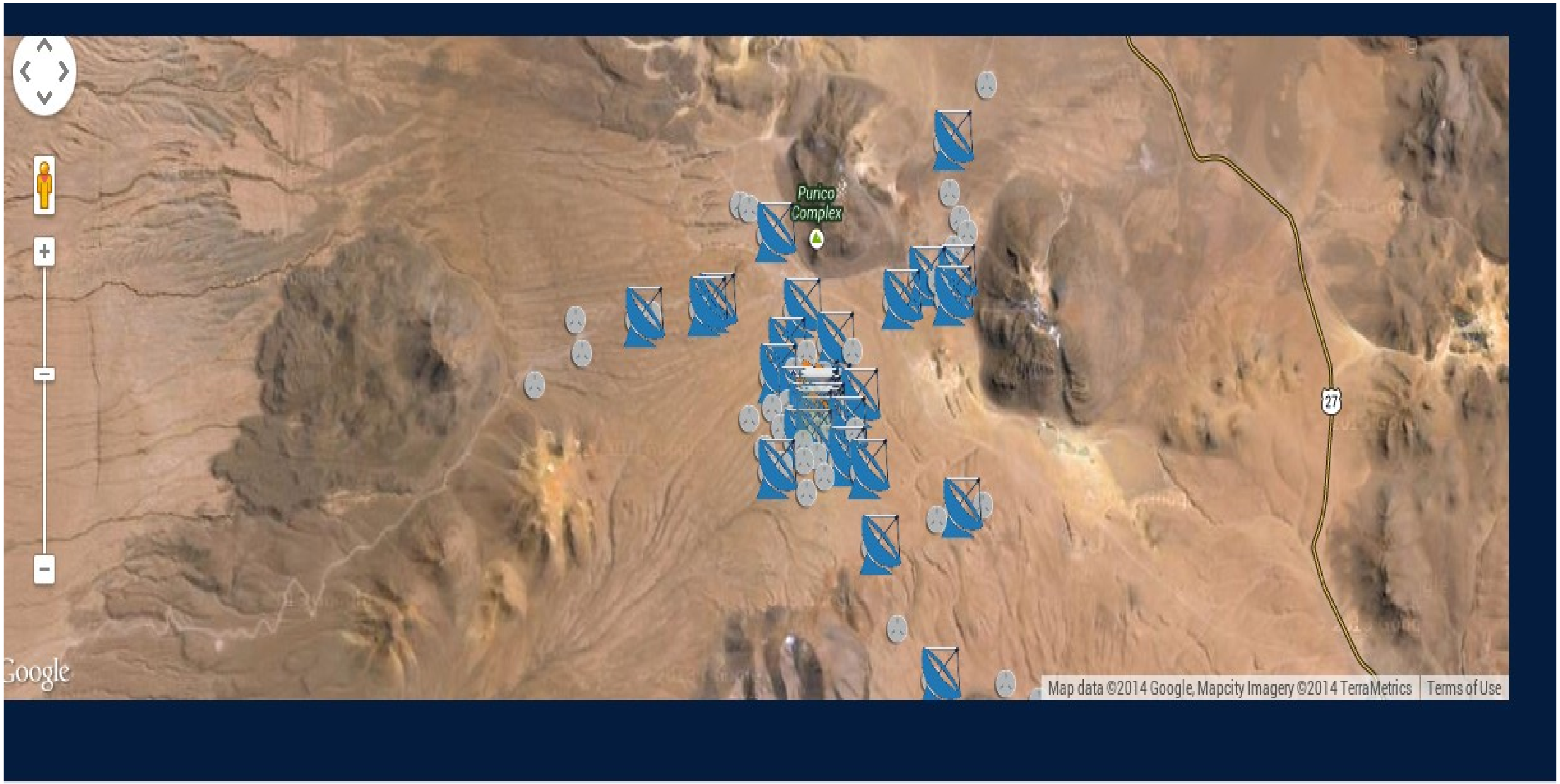
Antenna config expected (fixed ~10-km config until 7 Nov):



Resolution with Briggs 0.5

	10 km Array	5 km Array
Band 3	0.063’’	0.130’’
Band 4	0.042’’	0.086’’
Band 6	0.027’’	0.056’’
Band 7	0.018’’	0.037’’

Aerial View of ALMA on Sep 28



ALMA Selected Astrometric Projects

- Solar system Objects (asteroids and KB objects)
  ideal resolution for surface mapping
- Extra-solar planets
  expensive 5 hr x 20 over 5 yr. 400 stars, 0.2 mas accuracy
- Major Planet Gravitational/Mass Mapping
  egs. Io orbit Jupiter anomalies, Phobos orbit Mars anomalies
- Follow-up astrometric observations of ‘killer’ asteroids
  detected optically, accurate orbit determination with ALMA
- Parallax out to 1 kpc with 10% accuracy
  many objects or groups to do this on
- Relative motion/position of molecular lines in many objects
  only SNR limited since close in sky ~ Resolution/SNR
- Gaia/Stellar Position Comparisons with ALMA
  non-quasar comparisons with radio/optical

ALMA Astrometry

ALMA has great astrometric potential which is only now beginning to be realized.

Thank you