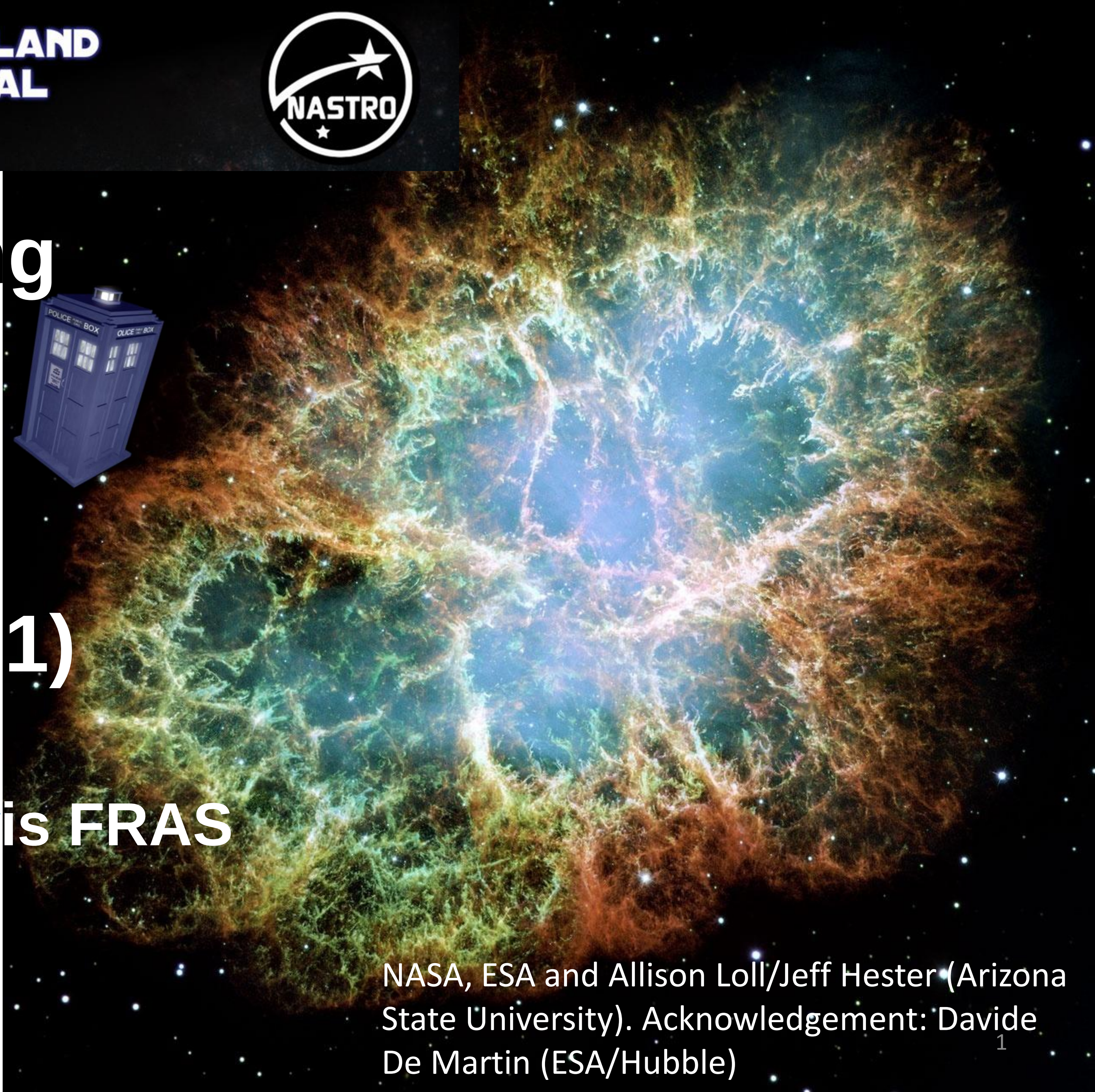
NORTHUMBERLAND ASTRONOMICAL SOCIETY

NASTRO

Measuring the Crab Nebula (Messier 1)



Dr Paul Lewis FRAS

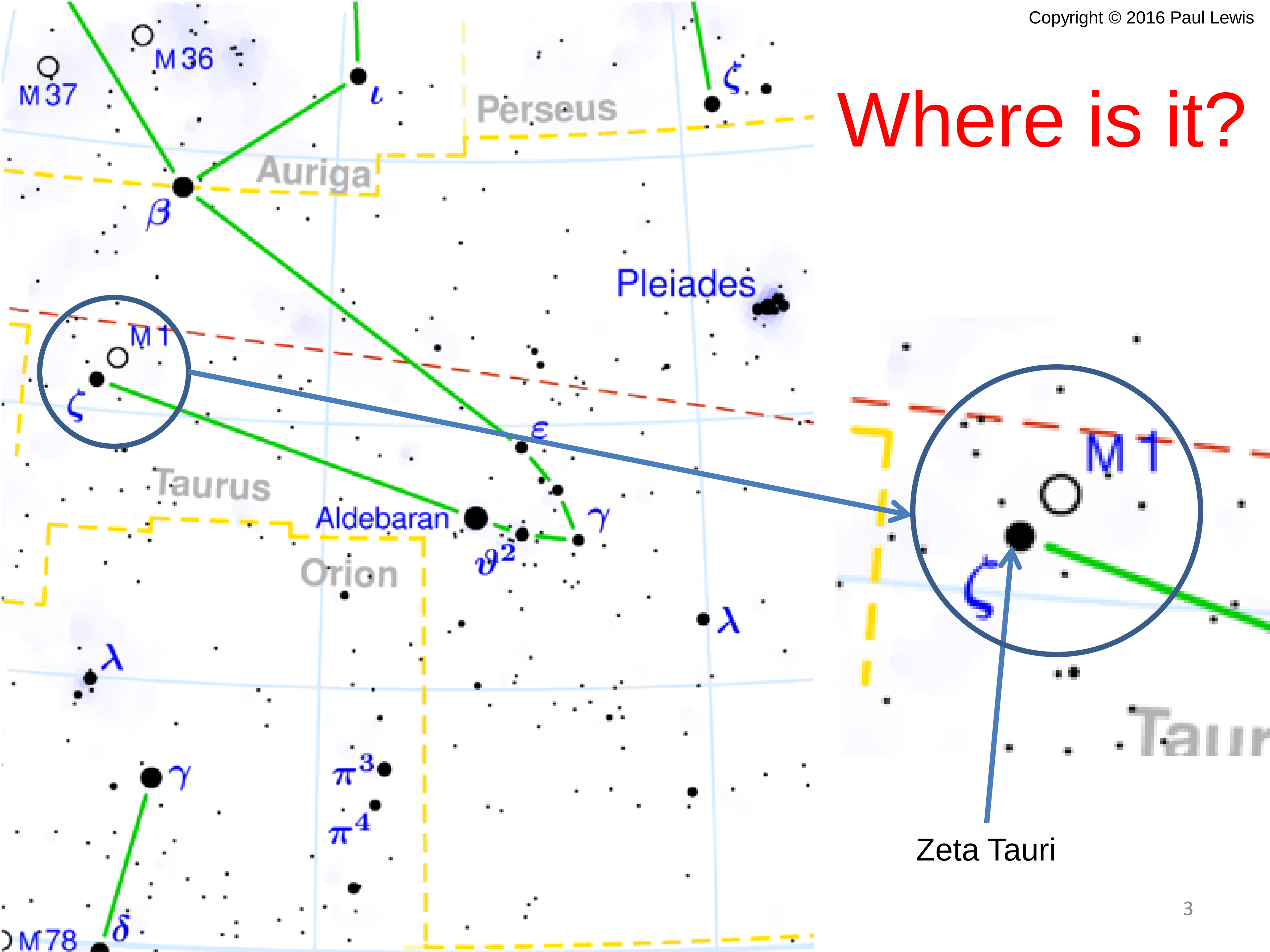
NASA, ESA and Allison Loll/Jeff Hester (Arizona State University). Acknowledgement: Davide De Martin (ESA/Hubble)

What is it?

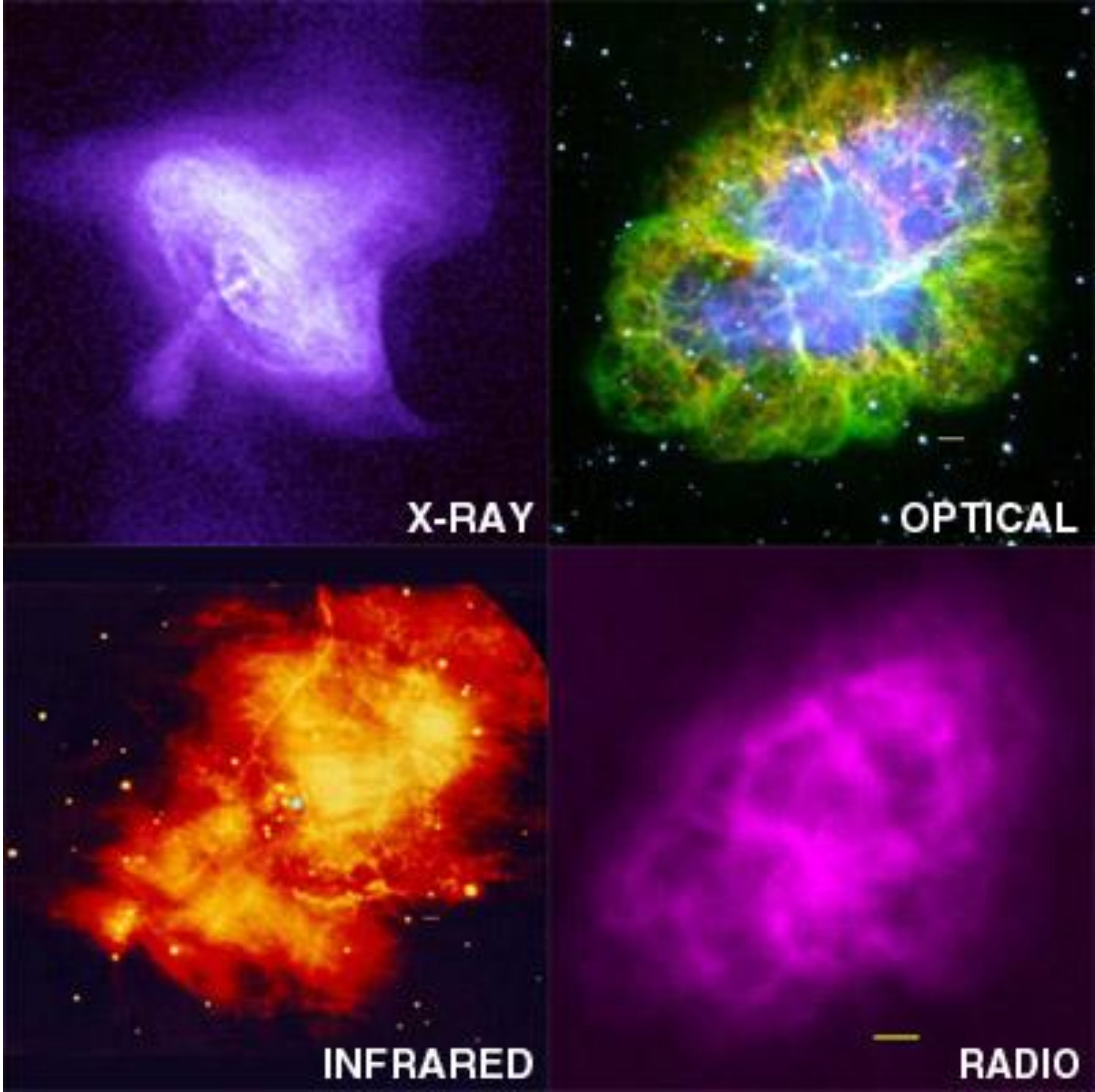
- Expanding remnant of supernova
- Reported by Chinese on 4th July, 1054
- Apparent magnitude: +8.4
- Distance: 6,500 light years (2,000 parsecs)
- Stellar remnant is pulsar
  - Neutron star that emits rapid and periodic pulses of radiation
  - Period 0.033 seconds
  - Rotates 30 times a second

In 1844 Lord Rosse published in the *Philosophical Transactions* a drawing made with his giant 72-inch reflector.

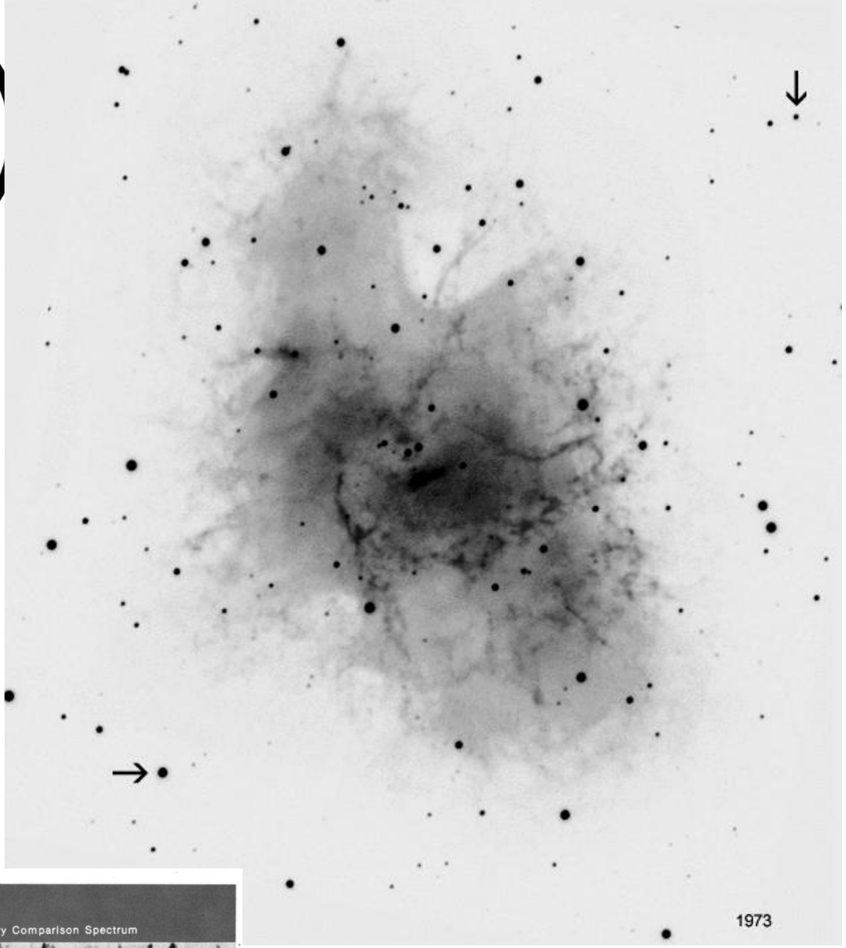
Where is it?

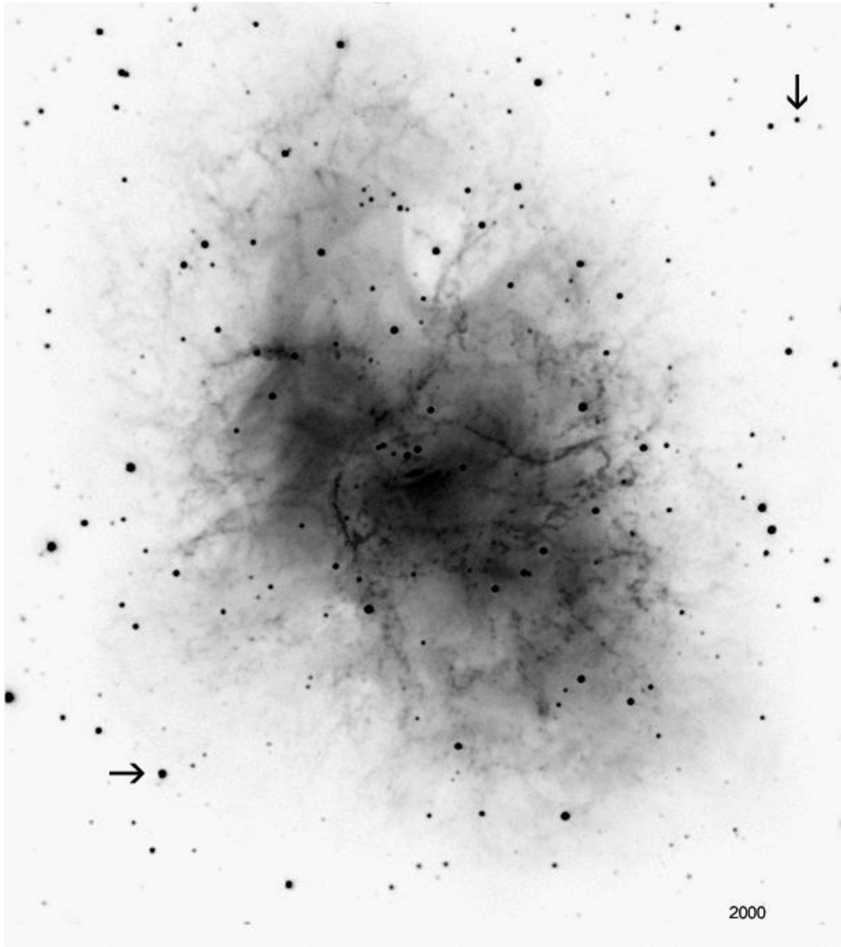

M 36
M 37
Perseus
Auriga
Pleiades
M 1
Taurus
Aldebaran
Orion
M 78
M 1
Taur
Zeta Tauri

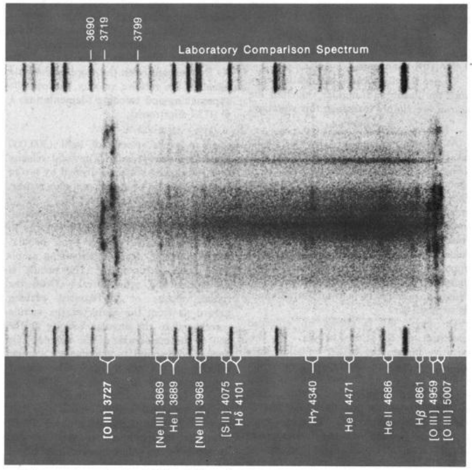
Different Wave-lengths



Equipment







The spectrum of the Crab nebula, obtained at Lick Observatory by N. U. Mayall with the Crossley reflector. The spectrograph slit was aligned with the major axis of the nebula (here vertical), to record velocity differences along that axis. These are best shown by the necklace shape of the 3727-angstrom oxygen line. A laboratory spectrum of palladium, tin, and lead flanks that of the Crab to give a wavelength scale; nebular lines are identified at bottom.

- ✯ Set square
- ✯ Ruler
- ✯ Pencil
- ✯ Calculator

Scientific approach

?

Objectives

1. Calculate age of nebula
   - Use the rate of expansion of the nebula by measuring the outward drift (proper motion)
2. Derive a distance to the nebula
   - Use the ‘expansion parallax’ method, which requires the radial velocities of the knots
3. Absolute magnitude
   - Use the value for the distance to derive the absolute magnitude of the supernova

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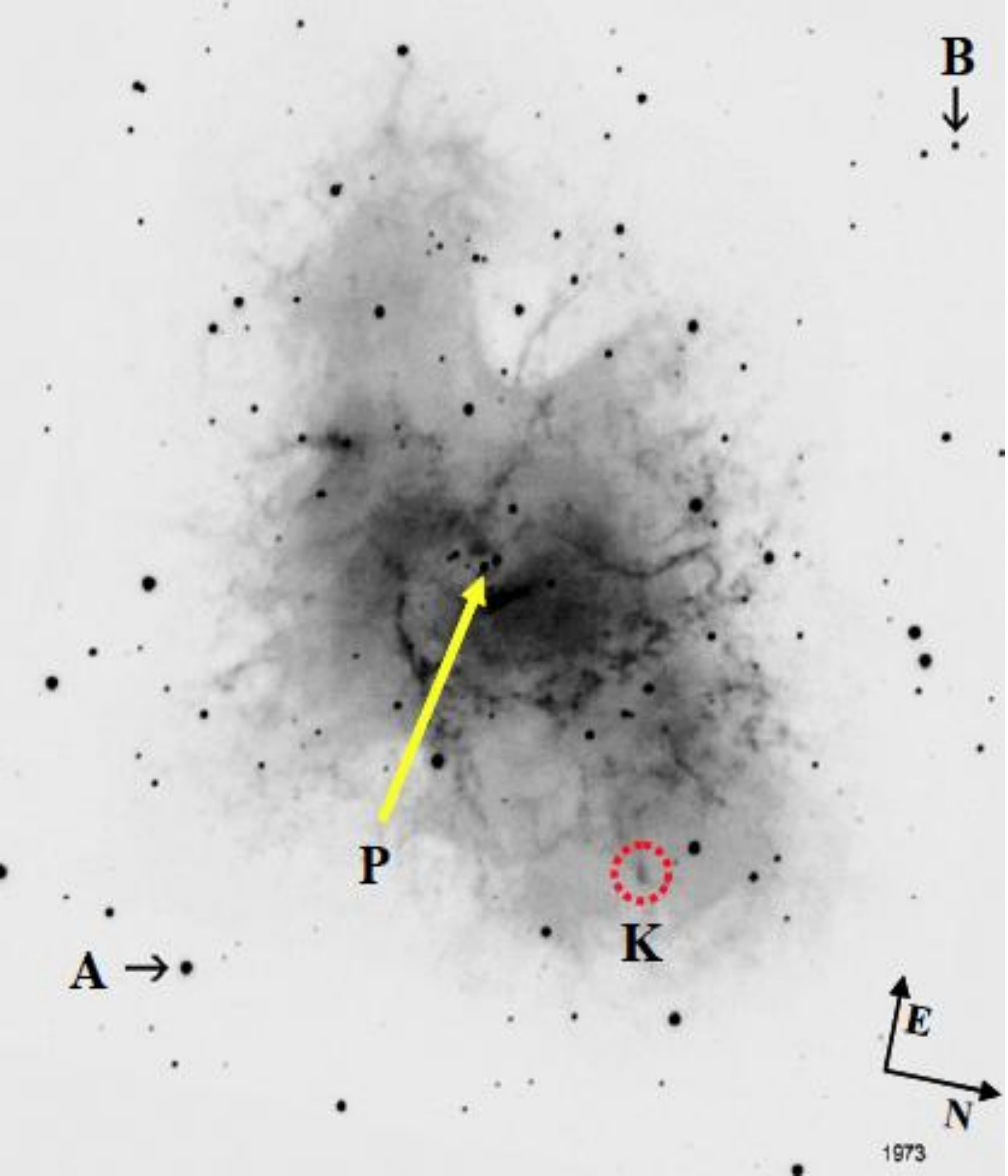
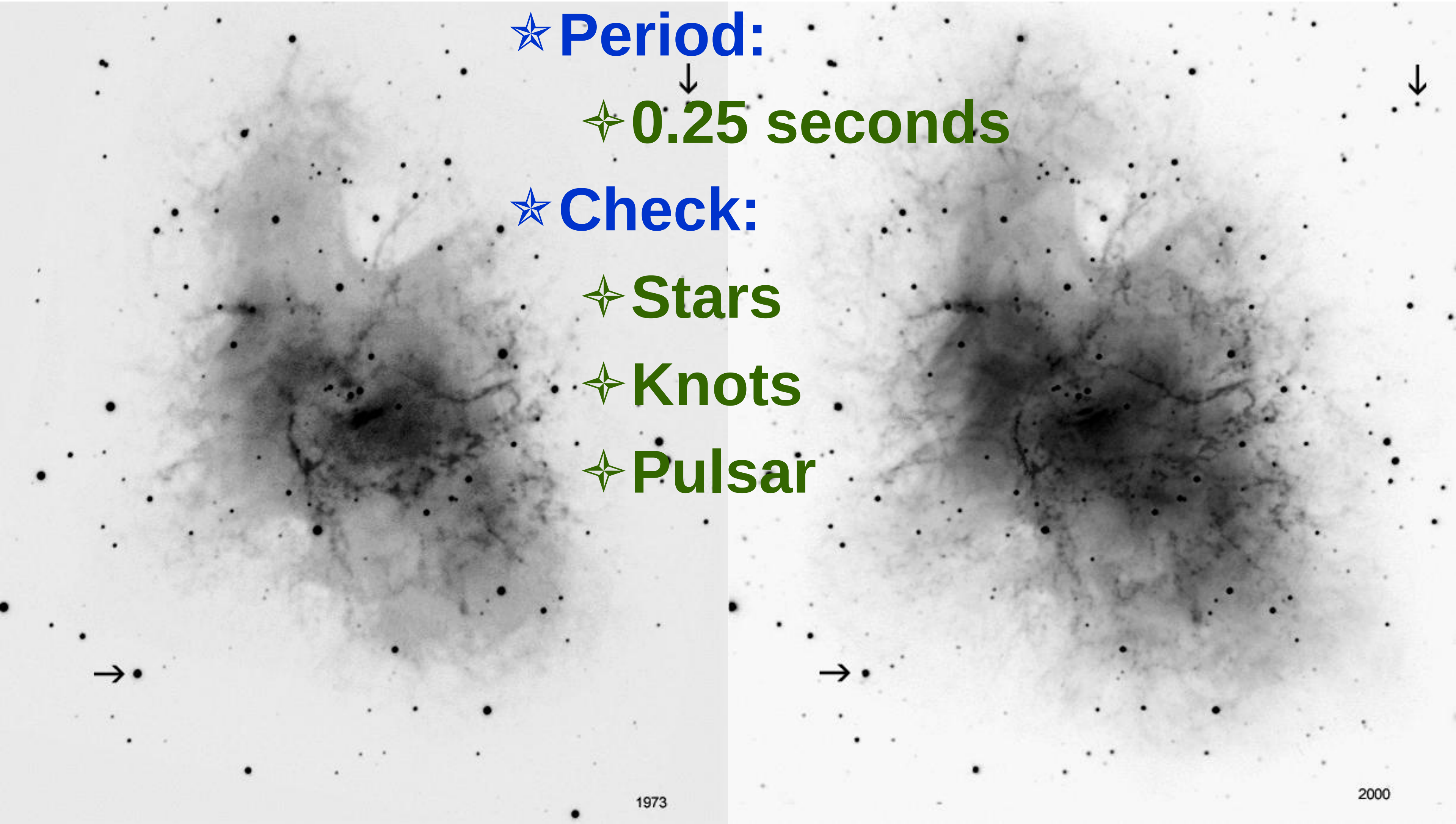
Finding the nebula's age



- Need two images 20 years or more apart
- Taken in 1973 and 2000 in red light (hydrogen)
- Identify comparison stars, pulsar and knots

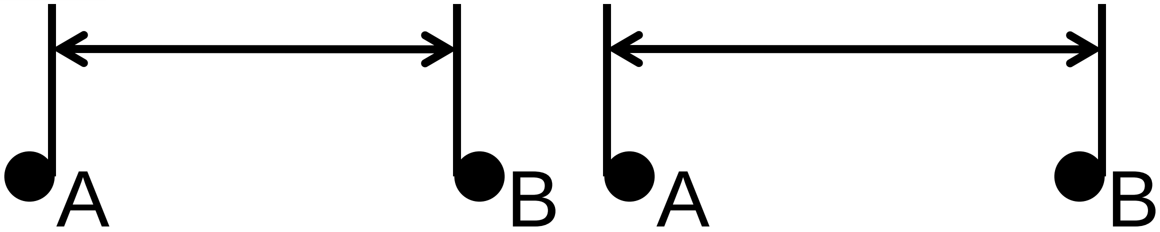
Blink comparison

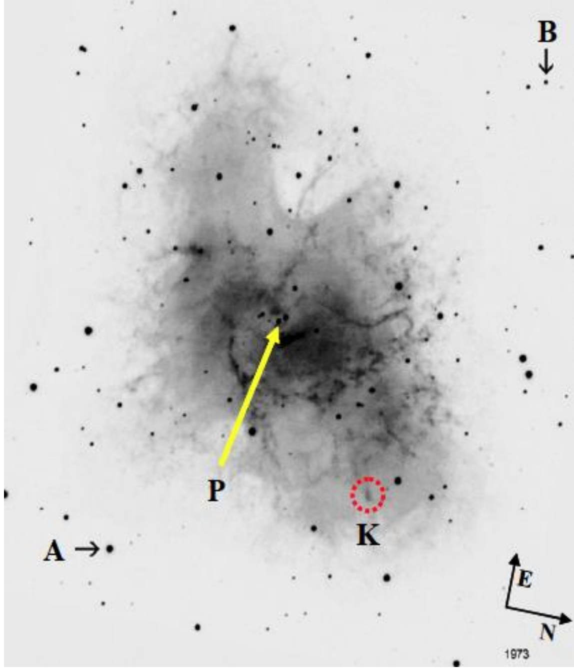
1973 2000



- Period:
  - 0.25 seconds
- Check:
  - Stars
  - Knots
  - Pulsar

Image scale





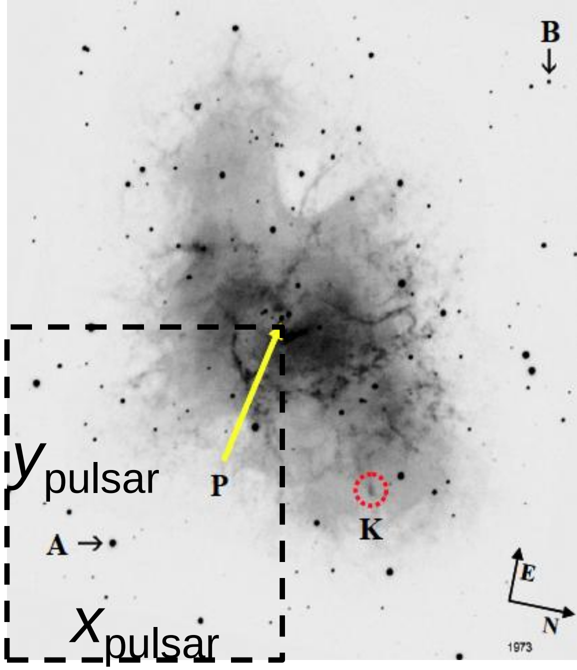
A and B are 385 arcseconds apart

$$\text{Image Scale} = \frac{\text{Angular separation (arcsecs)}}{\text{Linear separation (mm)}}$$

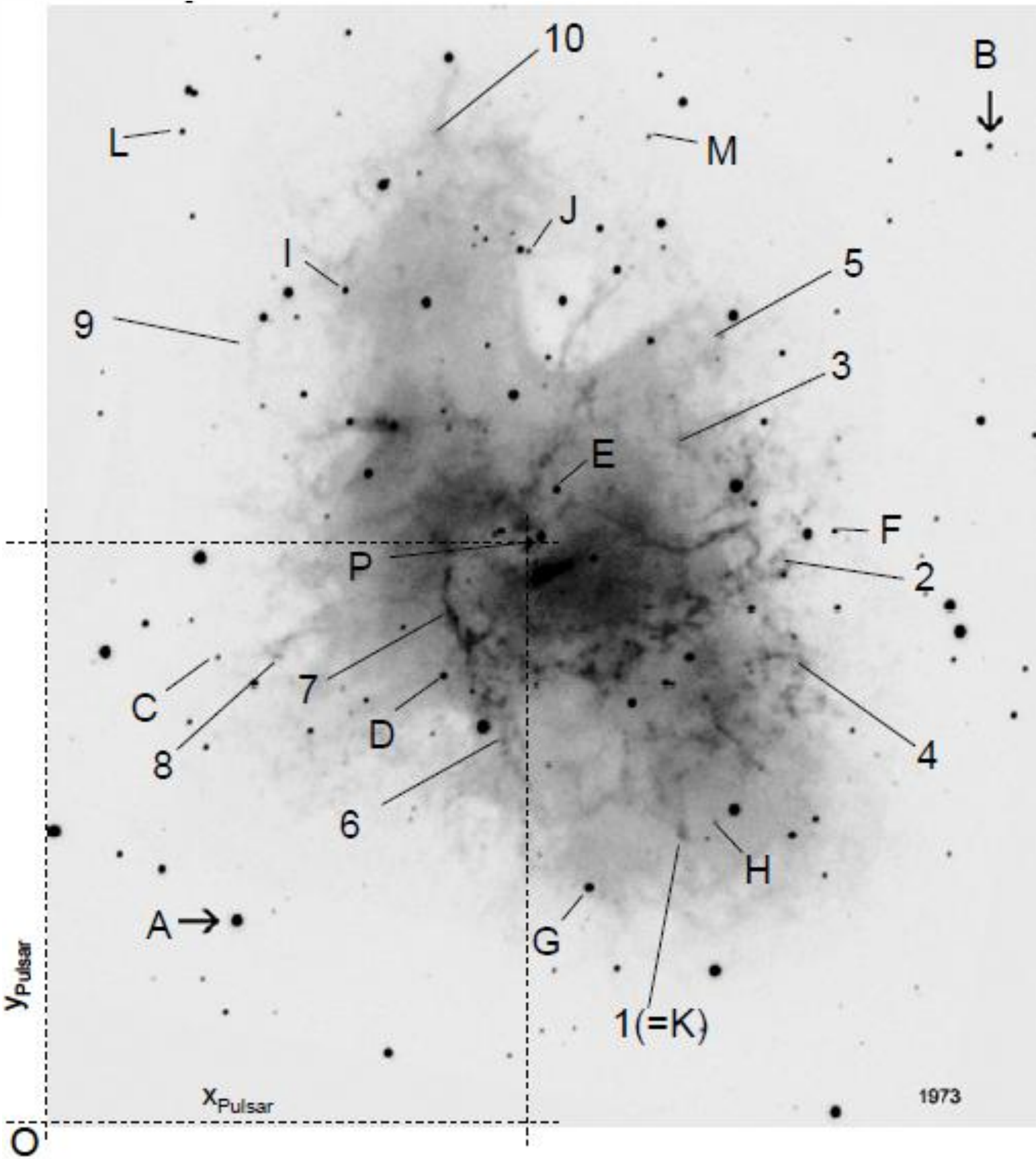
Star AB	Inner mm	Outer mm	Average mm	Image scale arcsec/mm	Plate scale arcsec/mm
1973	160.2	162.8	161.5	2.384	2.38 approx
2000	160.5	162.7	161.6	2.382	

Pulsar position

- Use set square
  - Construct lines parallel to edge
  - Passing through pulsar centre
  - Measure x_{pulsar} and y_{pulsar} using ruler
  - A check that pulsar correctly identified



	Pulsar Position	
Year	x_{pulsar} mm	y_{pulsar} mm
1973	71.3	87.2
2000	71.2	86.9



Comparison stars and knots

- Knots:
  - Numbered
- Stars:
  - Lettered

Comparison stars

- Check on precision of measurements
- Same technique as image scale
- Measure from pulsar
- Choose stars to cover most part of image
- Include A and B
- Include stars within image of nebula
- Fainter stars
  - Smaller images
  - Cleaner and easier to measure

Comparison stars

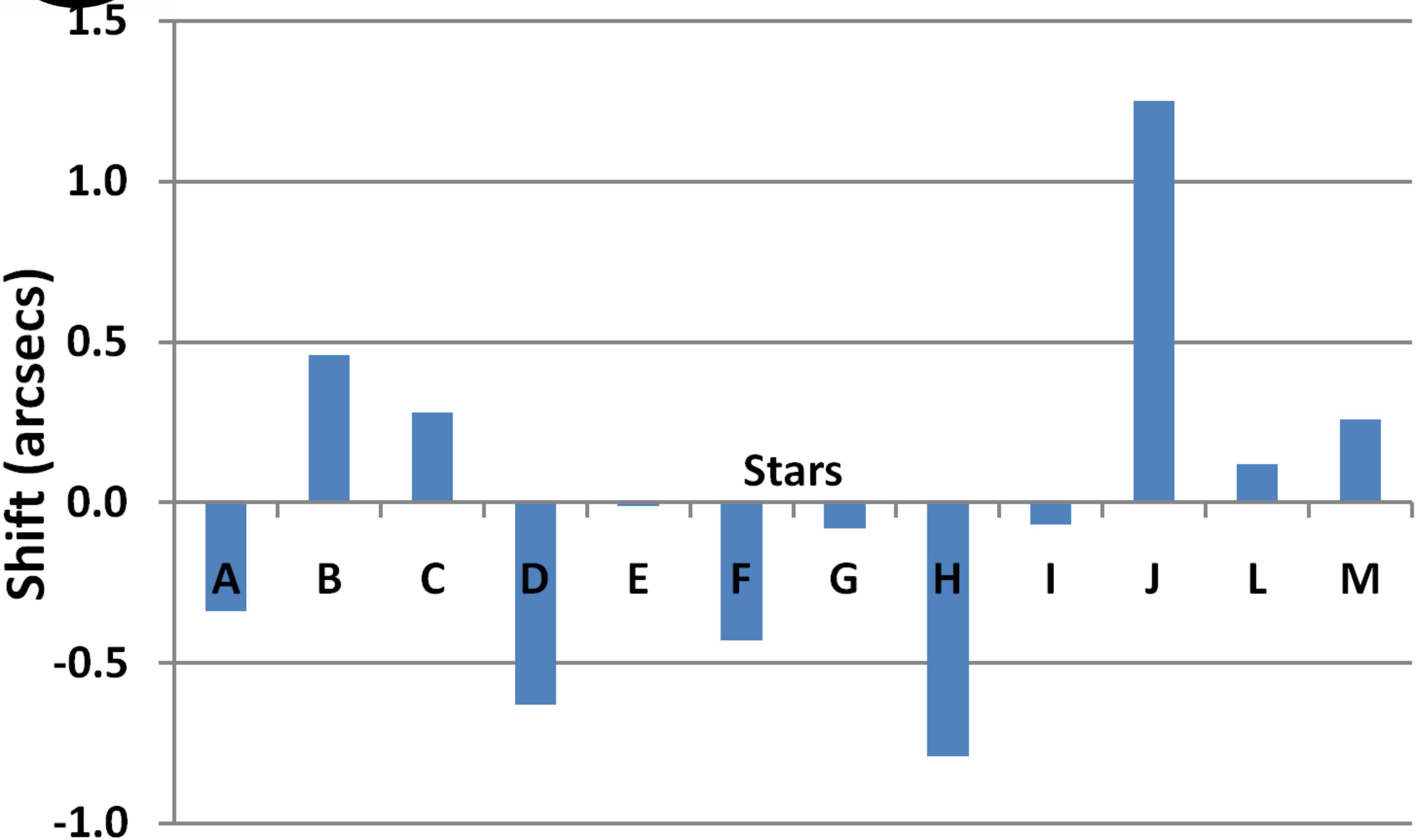
$$\text{Angular Distance (arcsec)} =$$

$$\text{Image Scale (arcsec/mm)} \times \text{Image Distance (mm)}$$

$$\text{Shift} = \text{Angular Distance (2000)} - \text{Angular Distance (1973)}$$

Stars	Shift (arcsecs)	Stars	Shift (arcsecs)
A	-0.34	G	-0.08
B	0.46	H	-0.79
C	0.28	I	-0.07
D	-0.63	J	1.25
E	-0.01	L	0.12
F	-0.43	M	0.26
Shift average		0.002 arcsecs	
Shift standard deviation		0.545 arcsecs	

Comparison stars

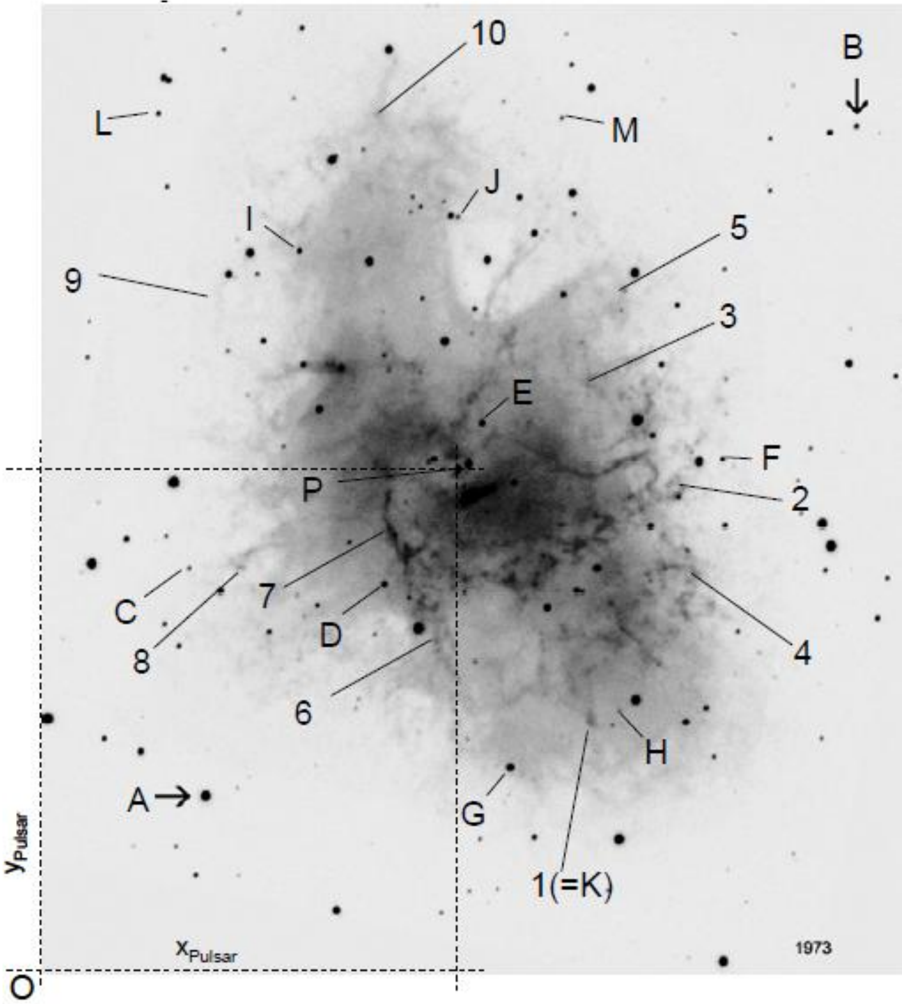


Comparison stars summary

- Most values well under 1 arcsecond
- No systematic movement of the stars between the two epochs
- Standard deviation suggests uncertainty in technique is about 0.5 arcseconds

Knots

- Measure from pulsar
- Difficulty in identifying the same part of knot on each image
  - Tend to change shape
  - Uncertainty larger than for stars



Calculations

- Shifts in knot position Δx (arcsecs)
  - Use image scale
  - Calculate angular separation from pulsar

$$\Delta x = x2000 - x1973$$

- Proper motion μ (arcsecs/year)

$$\mu = \frac{\Delta x}{\Delta t} \text{ where } \Delta t = 2000 - 1973 = 27$$

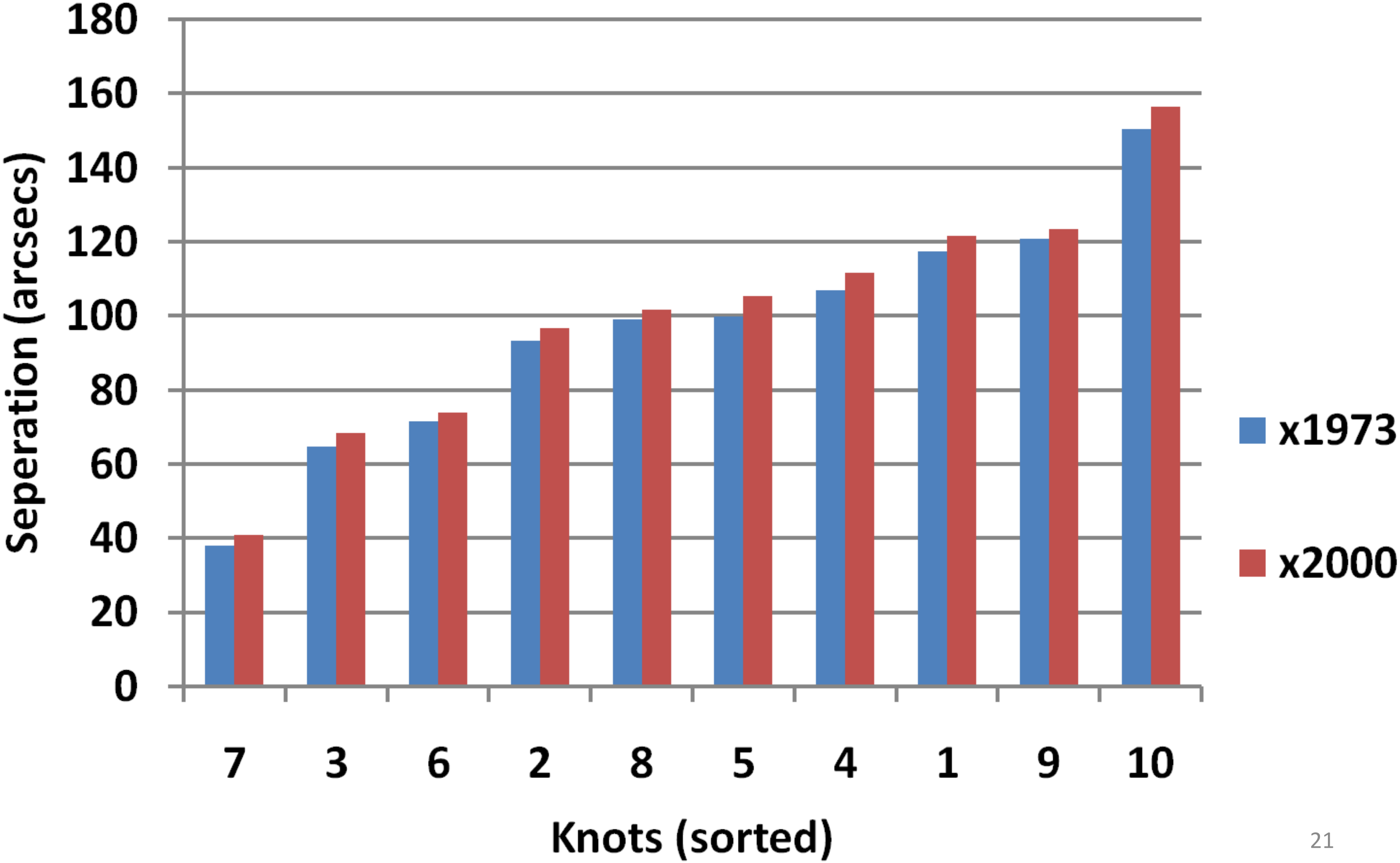
- Conversion time T (years)
  - Time taken to travel from pulsar
  - Assume current proper motion constant

$$T = x2000 / \mu$$

Separation of knots relative to pulsar

Knot	x1973 (arcsecs)	x2000 (arcsecs)
1	117.5	121.5
2	93.2	96.7
3	64.7	68.5
4	107.0	111.5
5	99.8	105.3
6	71.4	73.9
7	38.1	41.0
8	99.1	101.7
9	120.9	123.5
10	150.5	156.4

Separation of knots relative to pulsar



Proper motion

Knot	Shift Δx (arcsecs)	Proper motion μ (arcsecs/year)
1	3.98	0.147
2	3.52	0.130
3	3.77	0.140
4	4.46	0.165
5	5.54	0.205
6	2.45	0.091
7	2.84	0.106
8	2.68	0.099
9	2.66	0.099
10	5.86	0.217

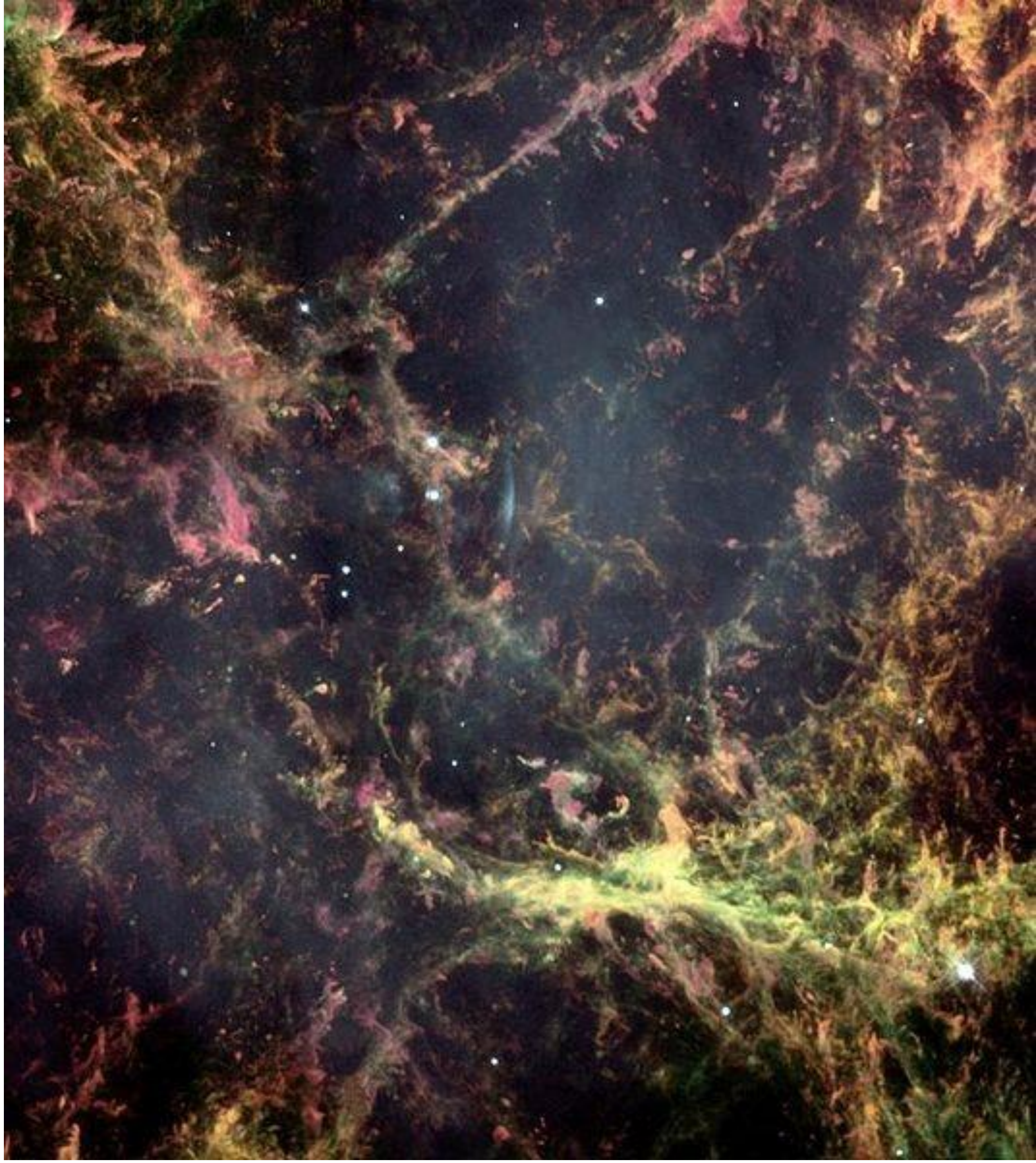
Time

Knot	Time (years)
1	825
2	743
3	490
4	675
5	513
6	811
7	390
8	1025
9	1252
10	720

- Time taken for each knot to travel from pulsar to position in year 2000
- Minimum time:
  - 390 years
- Maximum time:
  - 1252 years
- Average time:
  - 745 years
- Standard deviation:
  - 257 years

Date of supernova

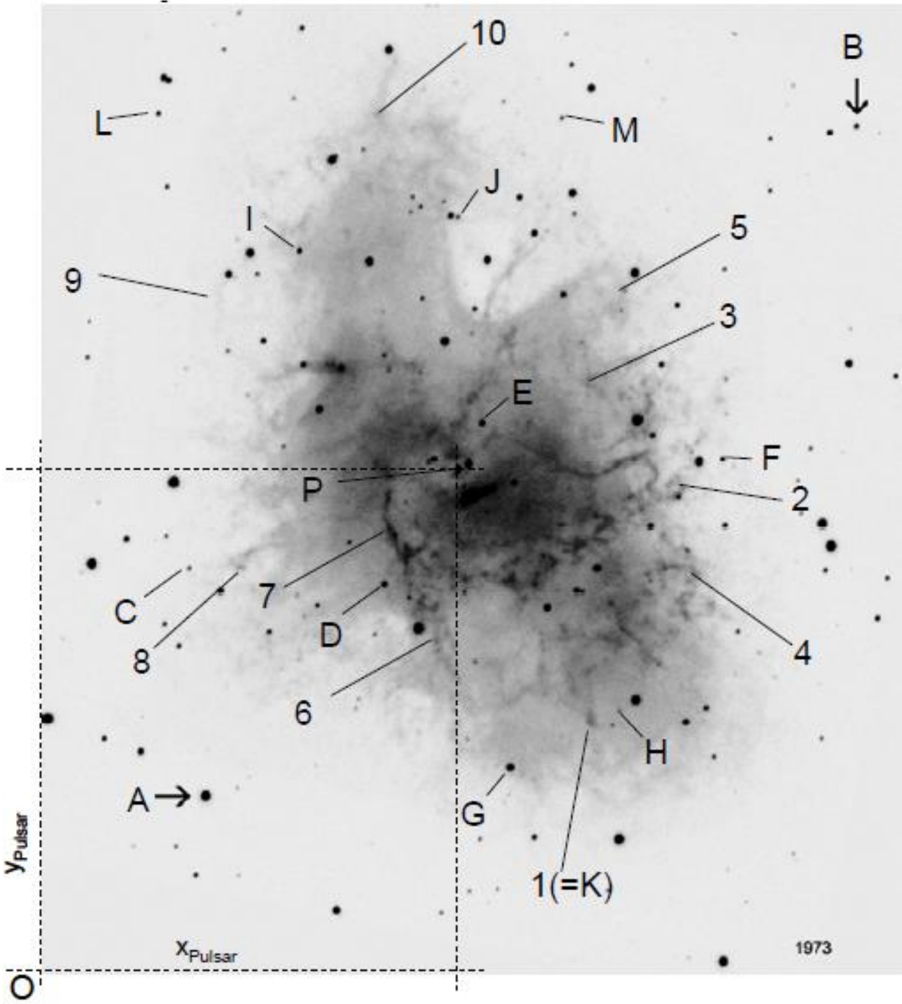
- Best estimate date:
  - 2000-745
- Calculated date:
  - 1255 AD
- Historical date:
  - 1054 AD



Hubble Space Telescope image of a small region of the Crab Nebula
Credit: NASA/ESA

Discussion

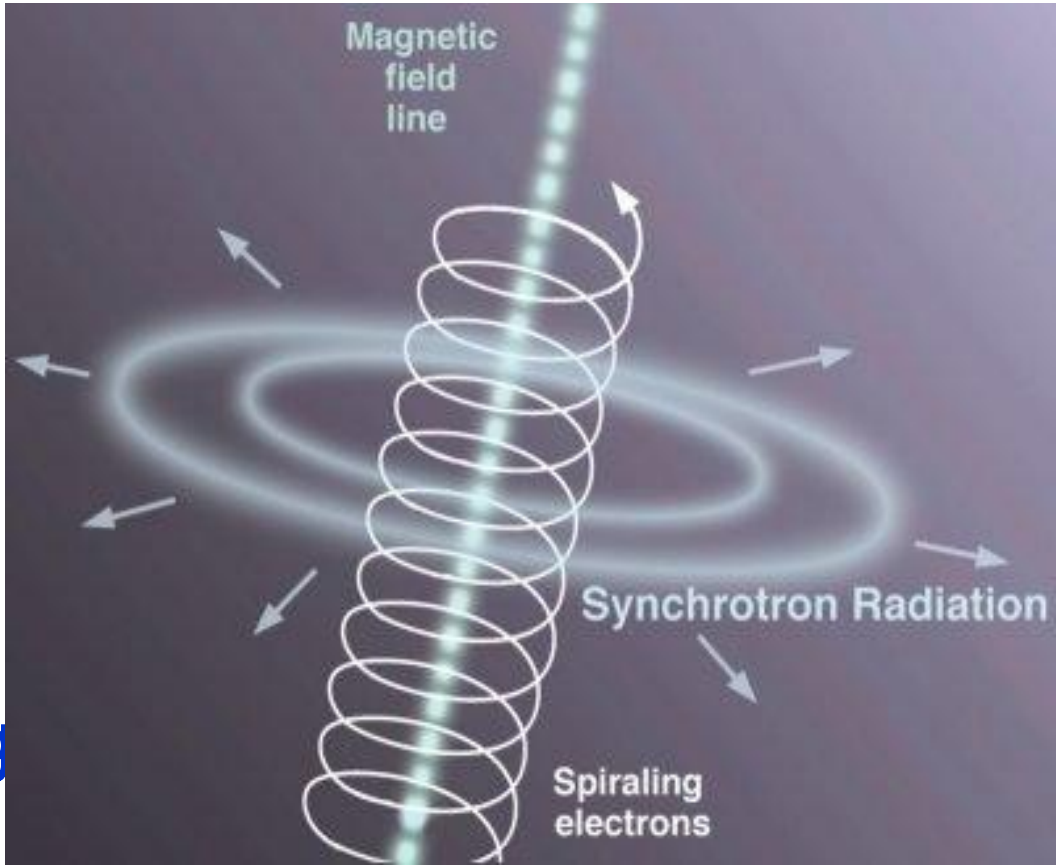
- Great variation in knot proper motion
- Measurement error quite large
- Unlikely more or better measurements would change result
- Therefore ejecta speed must be greater now than in the past
  - If travelling slower, take longer to reach present position



Ejecta speed

- Ejecta colliding with interstellar medium or debris from previous mass ejections
  - Expected to slow down
- To speed up
  - Must be some form of active acceleration
- Current explanation by Virginia Trimble: 1968
  - Electrons are accelerated in the magnetic field of the pulsar
  - Emit synchrotron radiation
  - Pressure from synchrotron nebula accelerates the knots

Synchrotron Radiation



- Synchrotron radiation is electromagnetic radiation generated by a synchrotron (particle accelerator)
- It is generated by the acceleration of ultra-relativistic (i.e. moving near the speed of light) charged particles through magnetic fields
- The radiation produced may range over the entire electromagnetic spectrum

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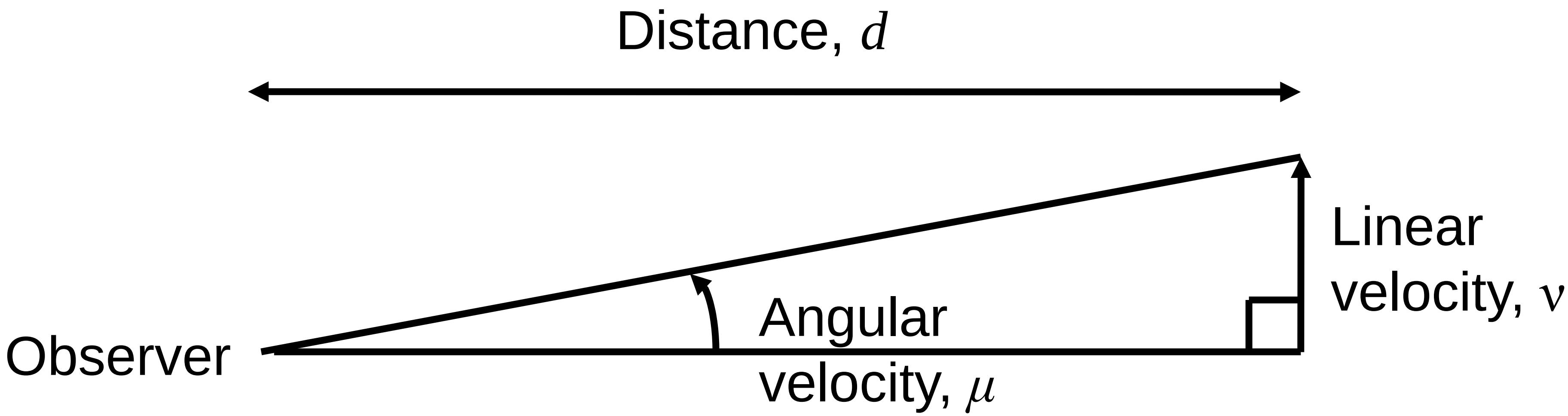
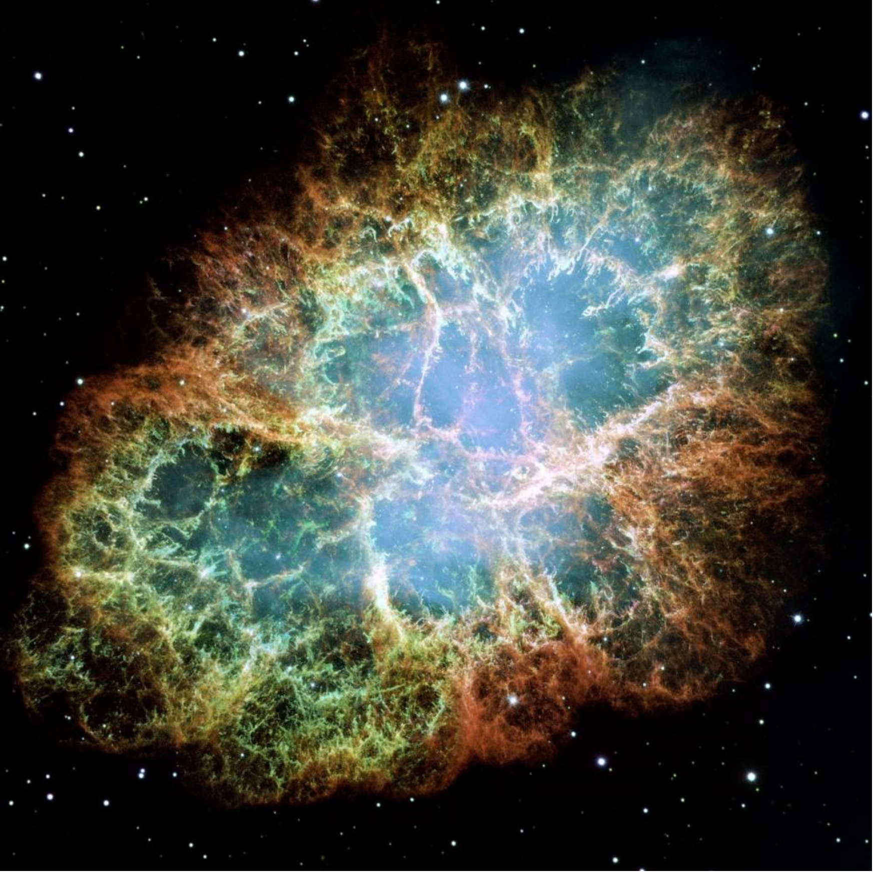
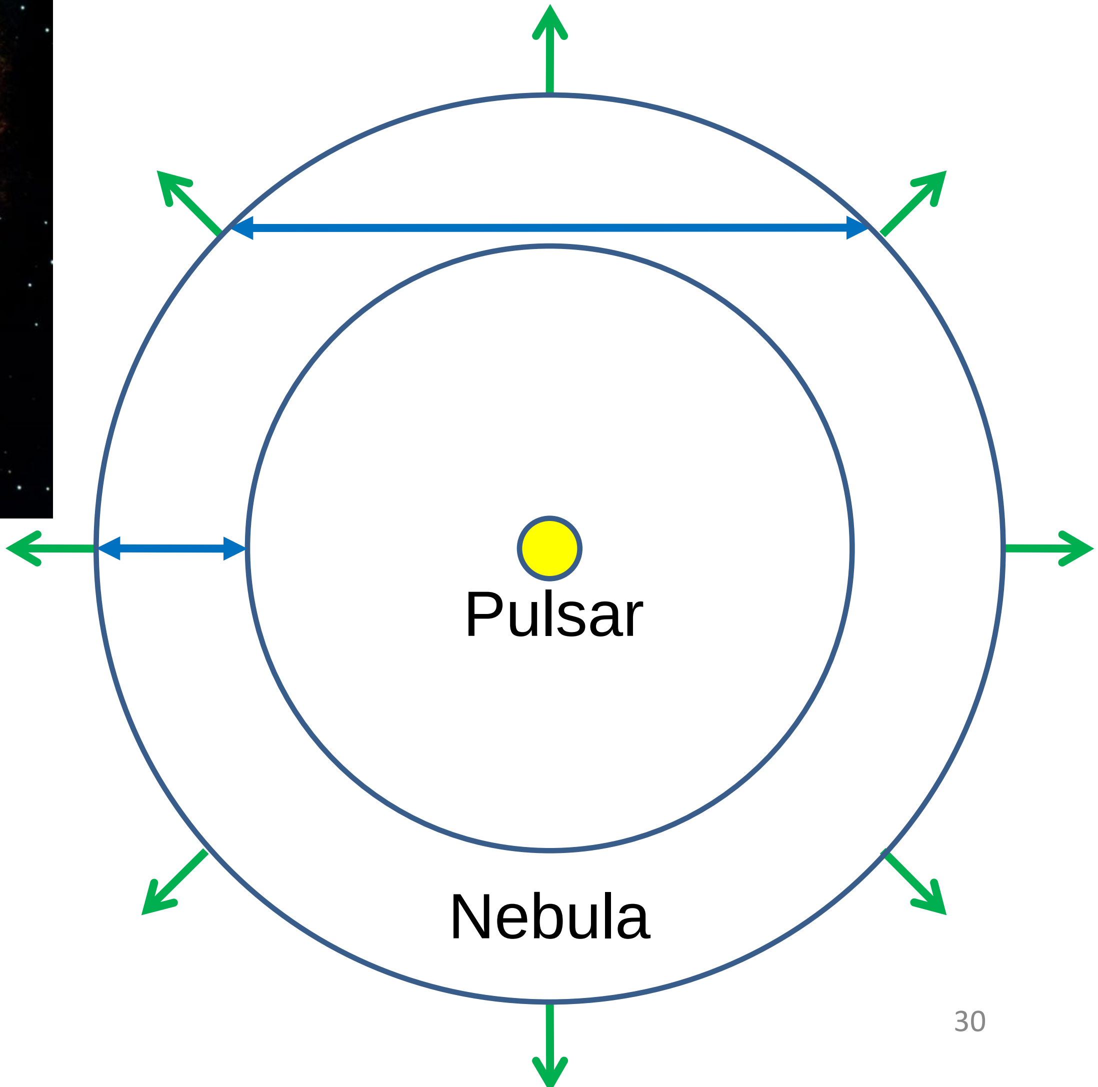
Expansion parallax



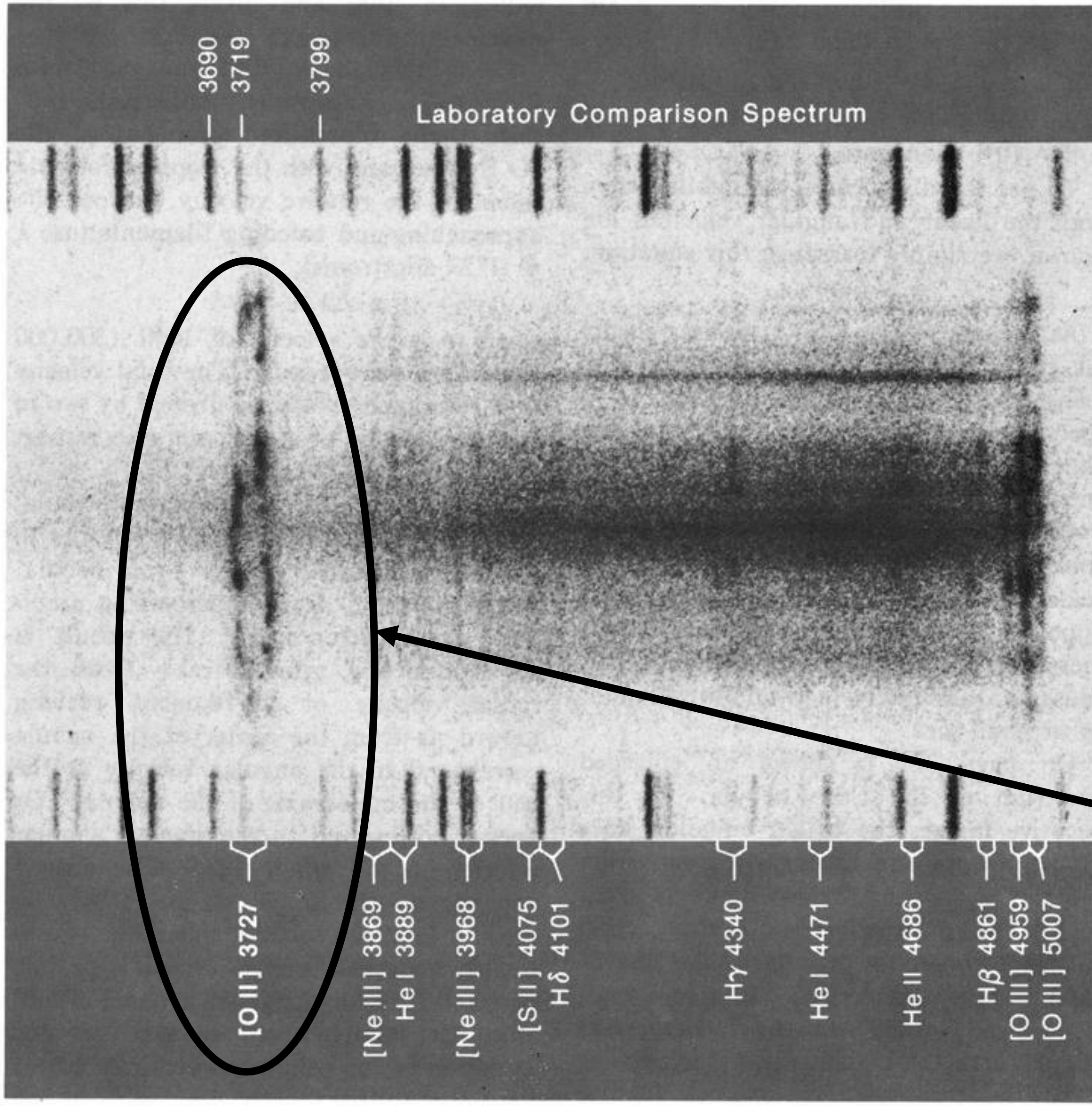
$$d\ (\text{parsec}) = \frac{v\ (\text{km/s})}{4.74 \times \mu\ (\text{arcsec/year})}$$

Crab nebula





Spectrum



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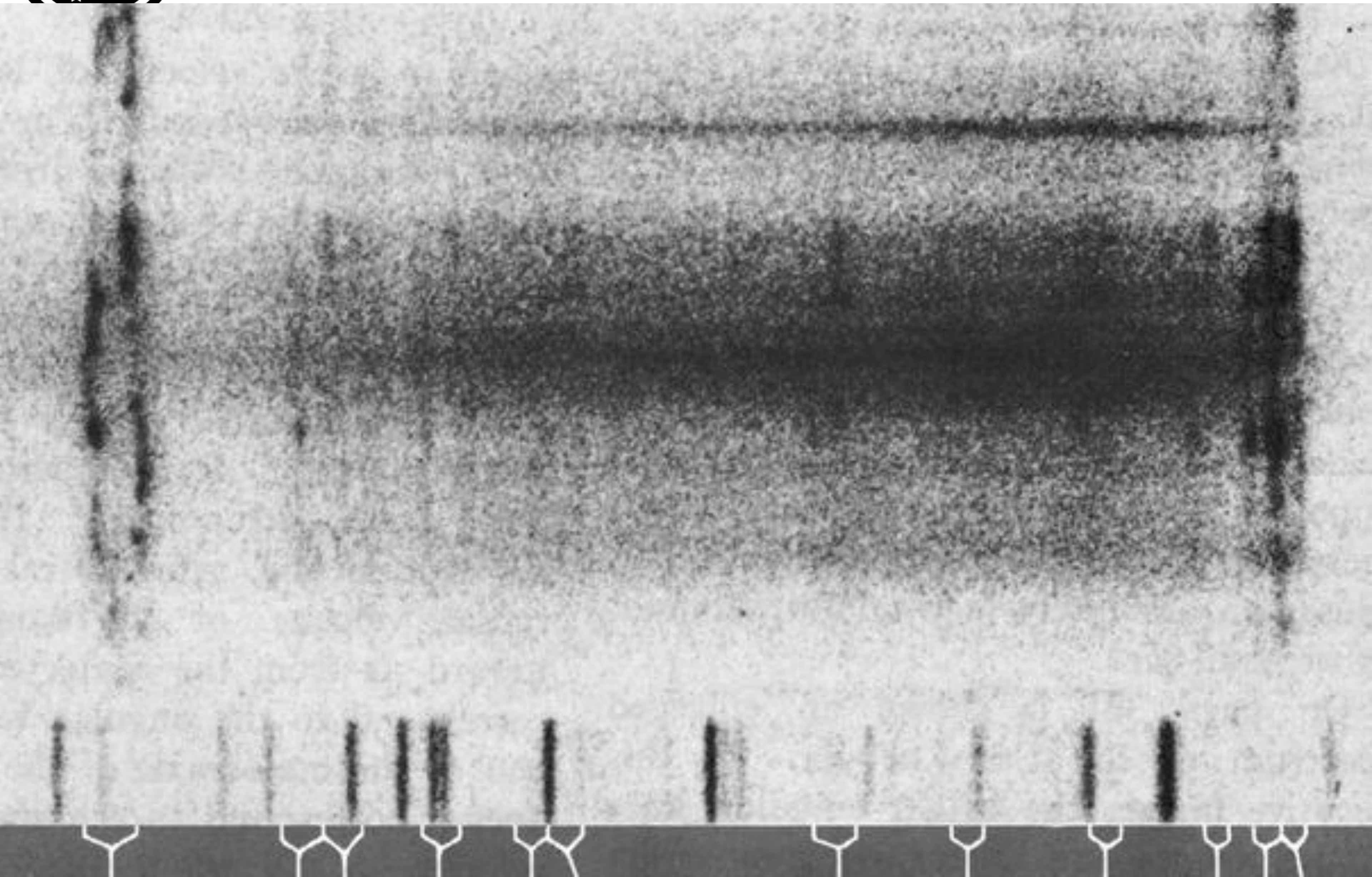
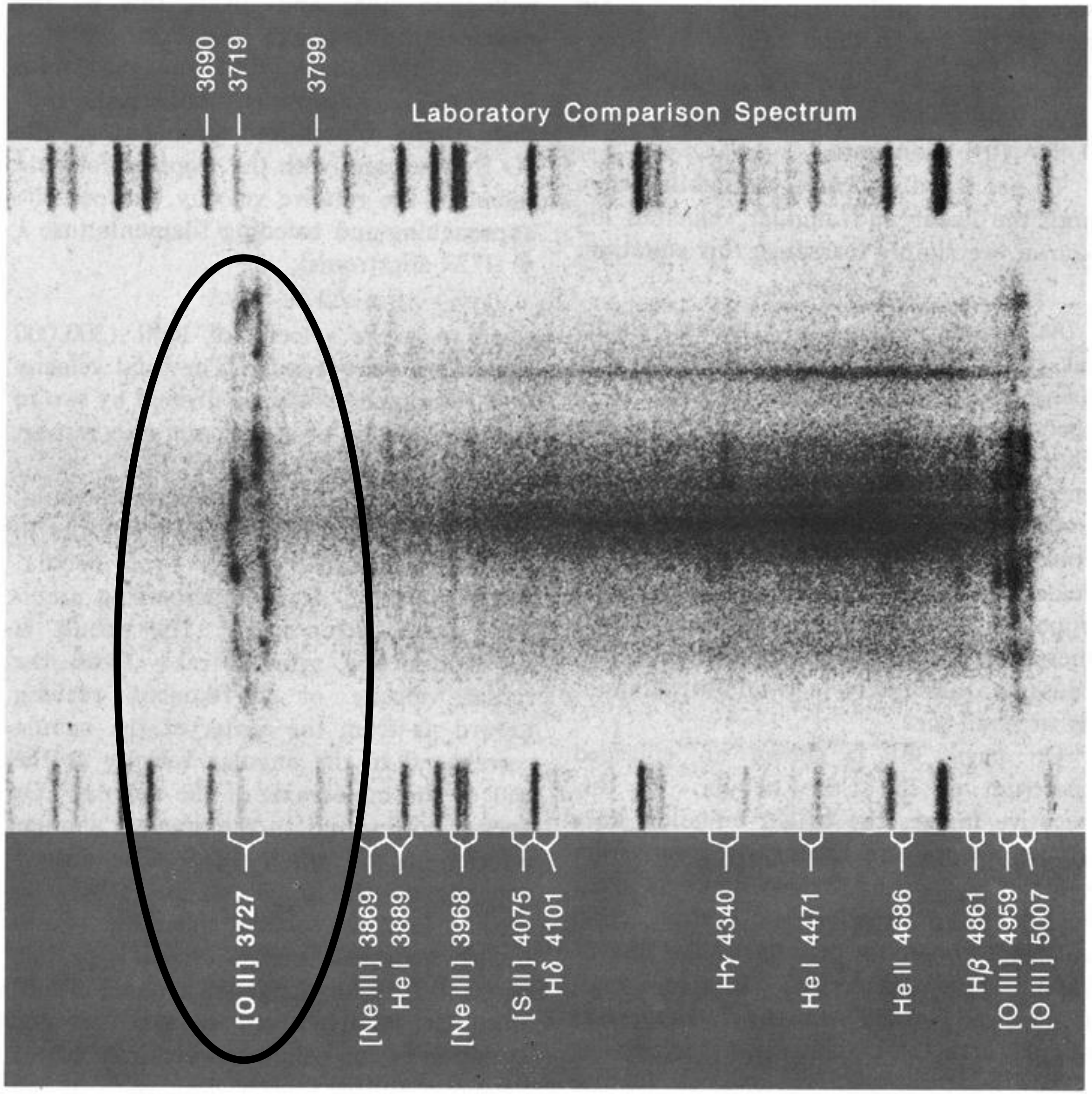
- Emission spectrum
- Negative image
- Slit aligned with Crab major axis
- Laboratory spectra (palladium, tin, lead)
- 372.7 nm ionised oxygen ‘necklace’
  - Red and blue shift
- Nebular lines along bottom

Emission lines





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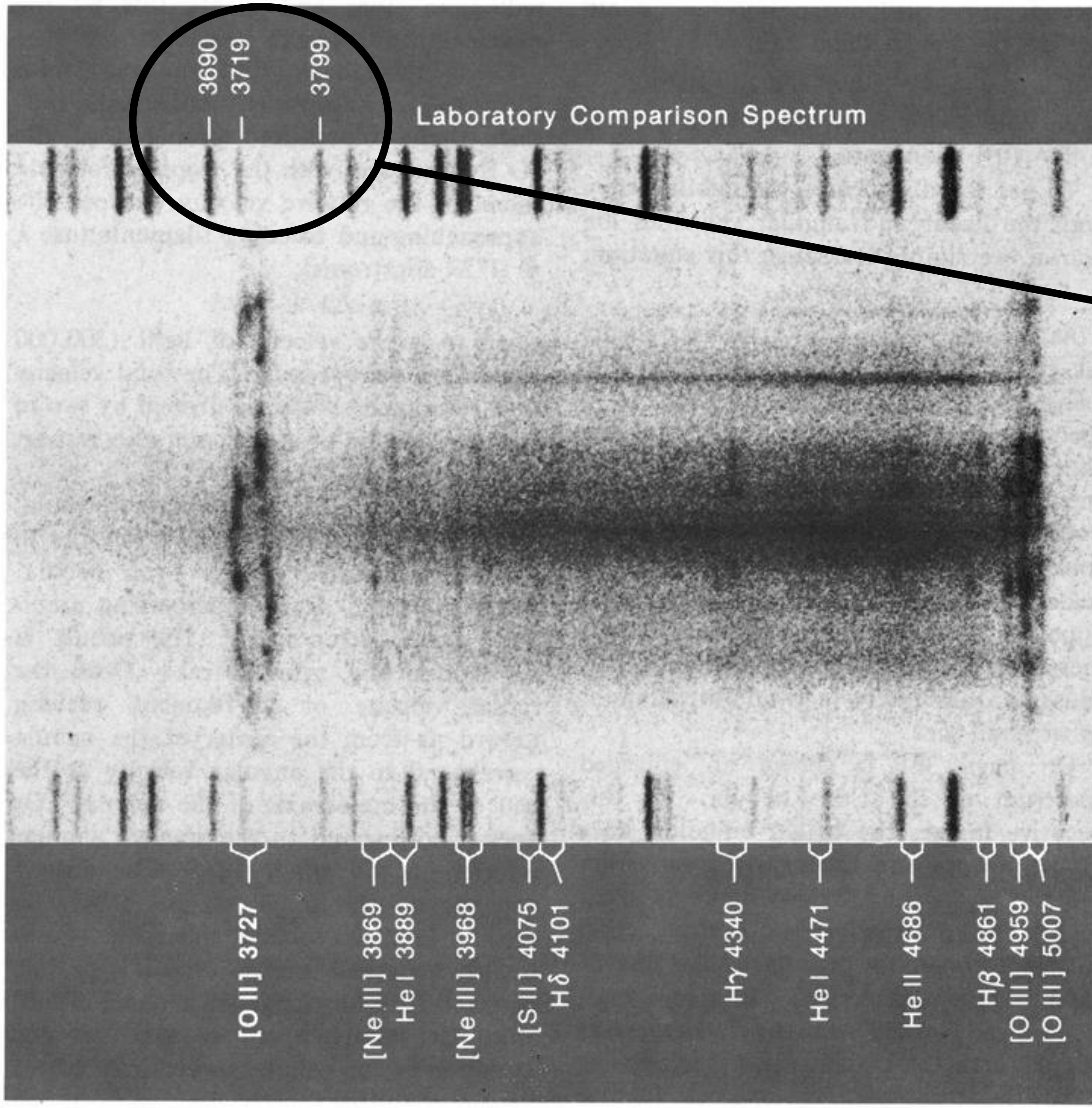
Oxygen line

- Most conspicuous emission feature
- Either red or blue shifted
- Filaments either front or far side
- Lie on outer edges of nebula
- Envelope with continuous synchrotron radiation inside

Dispersion



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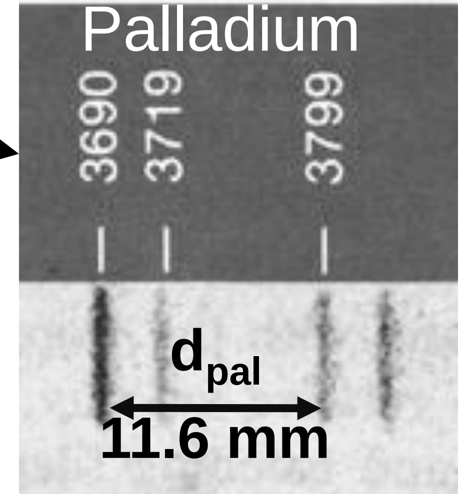


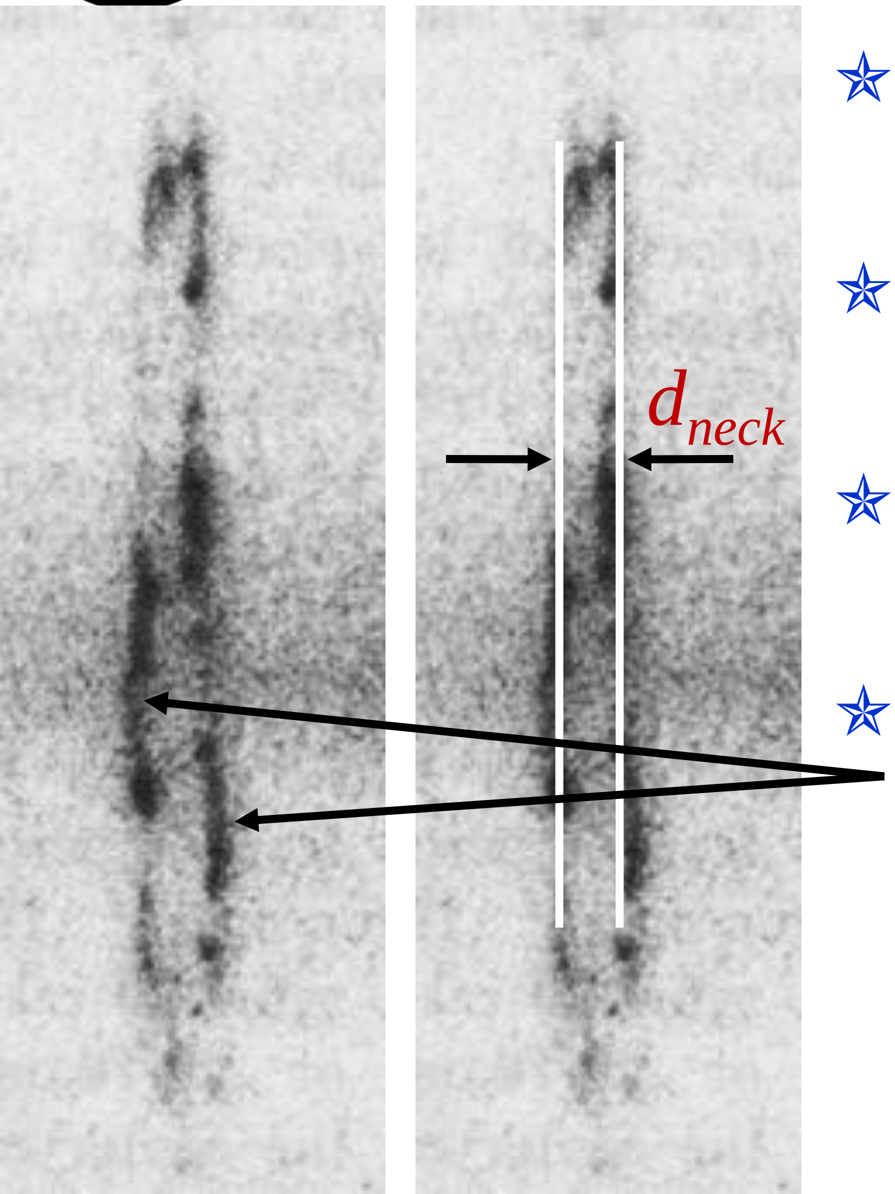
$$\Delta\lambda = 379.9 - 369.0$$

$$= 10.9 \text{ nm}$$

$$\text{Dispersion} = \frac{\Delta\lambda}{d_{pal}}$$

$$= \frac{10.9}{11.6} = 0.940 \text{ nm/mm}$$

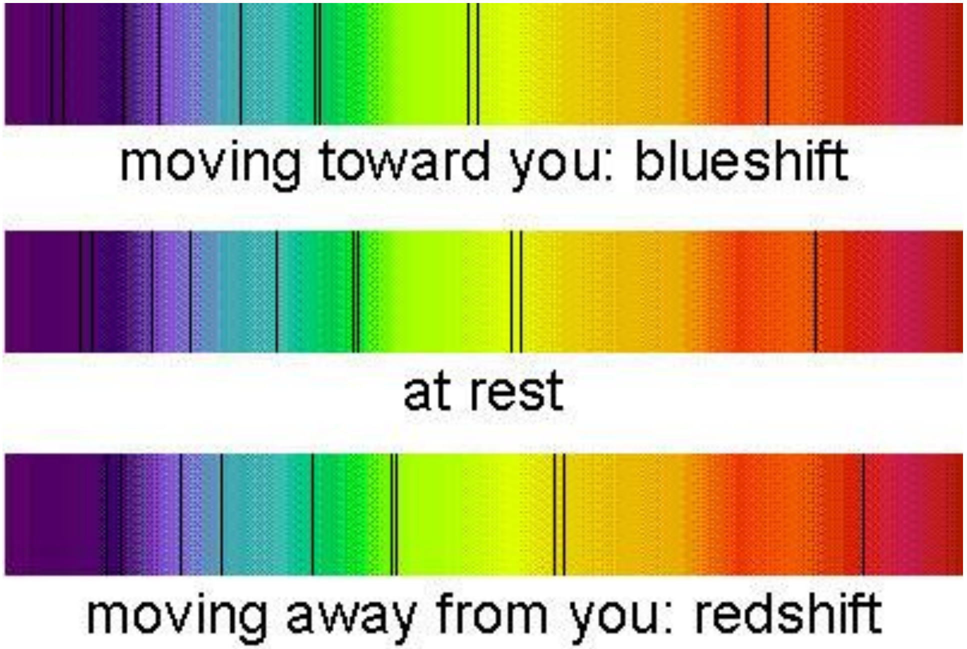
Measurement of OII line



- Not equally bright in all places
- Formed by images of individual knots
- Line drawn through centre of most red and blue shift
- Maximums in different positions

$$d_{neck}=3.8 \text{ mm}$$

Radial velocity



$$\text{Radial velocity} = \frac{\text{Change in wavelength}}{\text{Rest wavelength}} \times \text{Speed of light}$$

$$v = \frac{\Delta\lambda}{\lambda_0} c \text{ km/s}$$

Wavelength separation, $\Delta\lambda$

$$\Delta\lambda = d_{neck} \times \text{Dispersion}$$

$$\Delta\lambda = 3.8 \times 0.94 = 3.57 \text{ nm}$$

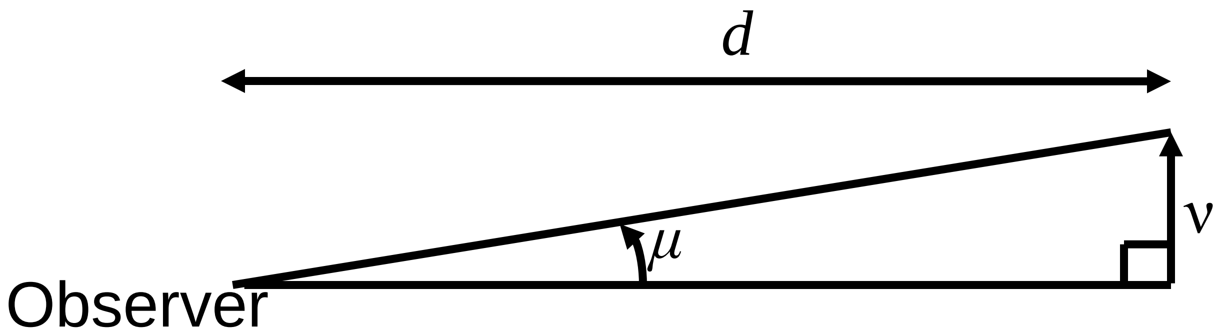
Radial velocity, v

$$v = \frac{\Delta\lambda}{\lambda_0} c$$

$$v = \left(\frac{3.57}{372.7}\right) \times 300{,}000 = 2870 \text{ km/s}$$

$$v_{pulsar} = (2870 \div 2) = 1435 \text{ km/s}$$

Distance, *d*

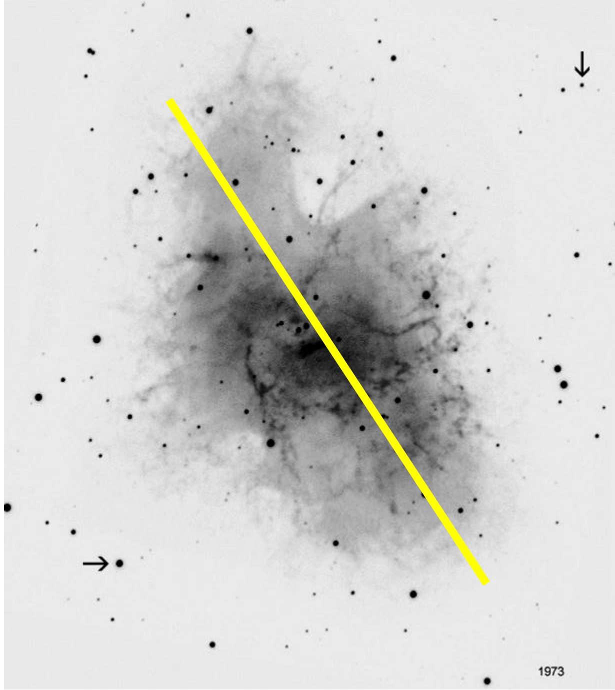


$$d\ (\text{parsec}) = \frac{v\ (\text{km/s})}{4.74 \times \mu\ (\text{arcsec/year})}$$

$$d = \frac{1435}{4.74 \times 0.140} = 2160\ \text{pc}$$

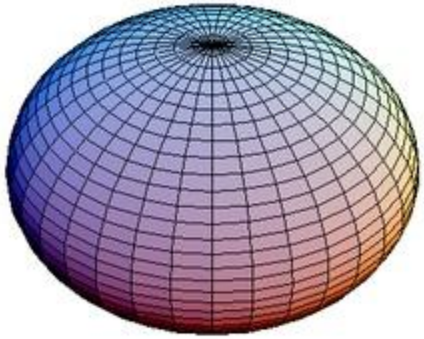
(μ is average angular velocity of knots from 'age' calculations)

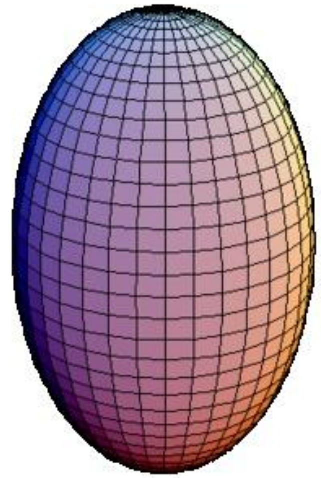
Comparison

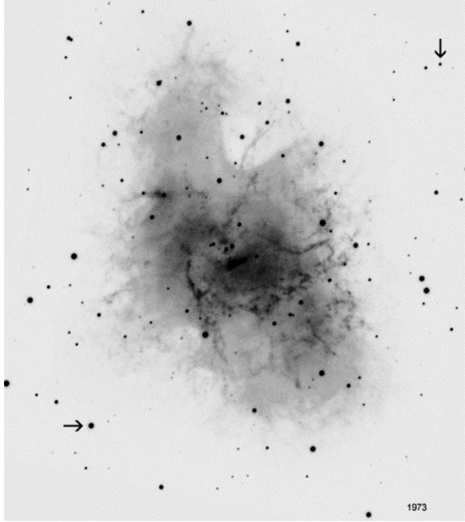


- Accepted value: 2000 pc
- Calculated value: 2160 pc
- Use knots more selectively?
  - Assumed radial velocity equal to average
  - True if spherical
- Nebula not spherical
  - What shape is it?

Shape







- Oblate spheroid
  - Polar axis shorter than the equatorial diameter
  - Smarties, M&M’s, Earth (slightly)
- Prolate spheroid
  - Polar axis greater than the equatorial diameter
  - Rugby ball shaped
- Highest radial velocities will underestimate speeds at end of major axis
- Correspond to lower speeds at ends of minor axis

Choice of knots

- Radial velocity
  - Using ends of minor axis
- Proper motion
  - Use knots at end of the minor axis
  - Ignore other knots
- Distance gives 2632 pc
- Not consistent with accepted value of 2000 pc
- Depends on which knots are used
  - Due to lack of spherical symmetry

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Magnitude

- Apparent magnitude, m_v
  - Brightness as seen
  - Depends on brightness, distance, dust
  - Sun: -26.74
- Absolute magnitude, M_v
  - Brightness at 10 pc (32.6 light years)
  - Sun: +4.83

Absolute magnitude

- Apparent magnitude at peak: $m_v = -4.0$
- Distance: $d = 2000$ pc
- Extinction from dust: $A_v = 3.0$

$$M_v = m_v - 5\log d + 5 - A_v$$

$$M_v = -4.0 - 5\log 2000 + 5 - 3.0$$

$$M_v = -18.5$$

- Type II supernova, typically M_v=-16.5

Magnitudes

- Difference between 2 magnitudes is 2.512

1st magnitude	2nd magnitude	Difference in magnitudes	Brightness difference
6	5	1	$2.512^1 \approx 2.5$
6	4	2	$2.512^2 \approx 6$
6	3	3	$2.512^3 \approx 16$
6	2	4	$2.512^4 \approx 40$
6	1	5	$2.512^5 \approx 100$
6	0	6	$2.512^6 \approx 250$
6	-1	7	$2.512^7 \approx 630$

Brightness of Crab Nebula

- ✯Absolute magnitude of Sun = 4.83
- ✯Absolute magnitude of Crab Nebula = –18.5
- ✯Difference in magnitude = 4.83 –(–18.5)≈23.3

$$2.512^{23.3} = 2 \text{ billion}$$

$(2.512^{23} = 1.5$ billion, $2.512^{24} = 4$ billion$)$

Absolute magnitude of the Crab Nebula supernova was about 2 billion times brighter than the absolute magnitude of the Sun

Conclusions

1. Calculate age of nebula
   - Shows expansion driven by radiation
2. Derive a distance to the nebula
   - Depends on data used
3. Absolute magnitude
   - Explains why seen during day