Title: Recent Results on the Famous Black Hole Binary Cygnus X-1

Speakers: Jerome Orosz

Series: Strong Gravity

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Abstract: The X-ray source Cygnus X-1 was discovered by sounding rockets in 1964 and is perhaps the oldest and best known "black hole candidate".   Its celestial coordinates were poorly known until 1971, when simultaneous radio flares and X-ray flares were observed which enabled the X-ray source to be associated with a 9th magnitude O-star known as HDE 226868. This star was subsequently shown to be a single-lined spectroscopic binary with an orbital period of about 5.6 days. However, owing to difficulties with measuring the system geometry and the distance to the source, the mass of the dark companion remained elusive. In 1974, Stephen Hawking and Kip Thorne famously made a wager on the nature of the dark companion in Cygnus X-1, with Hawking wagering that the dark companion was not a black hole. Eventually the consensus was that Cygnus X-1 does indeed contain a black hole, and Hawking conceded the bet in 1990.   In the following years many estimates for the black hole mass appeared in the literature, and most of them had large uncertainties, mainly owing to the difficulty of measuring the distance to the source. In this talk I will describe how we were able to use VLBI radio observations to measure a precise distance to the source, and how, in turn, this precise distance allowed us to obtain precise masses for the component stars in Cygnus X-1. Using the refined distance and geometry of the binary, it is possible to measure the relativistic spin parameter a* of the black hole using the X-ray continuum fitting technique. We find that the black hole spin is nearly maximal with a* > 0.9985 (3Ïƒ).

Recent Results on the Famous Black Hole Binary Cygnus X-1

Jerome A. Orosz

San Diego State University

jorosz@sdsu.edu

April 15, 2021

Credits

Thanks to:

- Jeffrey McClintock†, Mark Reid, (CfA)
- James C. A. Miller-Jones, Arash Bahramian (Curtin University)
- Thomas J. Maccarone (Texas Tech University)
- Lijun Gou, Xueshan Zhao (University of Chinese Academy of Sciences, Beijing)
- Janusz Ziółkowski (Nicolaus Copernicus Astronomical Center)
- NSF, NASA ($$$)
- John Hood, Jr. ($$$)

Overview

1. Introduction to Black Holes
    - Observer's Definition of a (Stellar) Black Hole
    - Number of (Stellar) Black Holes in the Milky Way
    - How to Detect (Stellar) Black Holes
    - What Black Hole Properties can we Measure?
2. Cygnus X-1
    - Discovery, Early History
    - Previous Work, or "Why is it so Hard?"
    - 2011 Results
    - 2020 Updates
        - Implications for Black Hole Spin
        - Implications for the Formation

Observer's Definition of a (Stellar) Black Hole

- In Main Sequence stars, the heat pressure balances the gravitational attraction.
- After the nuclear fuel is used up, the fate of the star's core depends on its mass:
    - $M_{\rm core} \leq M_{\rm Ch} \rightarrow$ white dwarf
    - $M_{\rm Ch} > M_{\rm core} \leq M_{\rm NS} \rightarrow$ neutron star
    - $M_{\rm core} > M_{\rm NS} \rightarrow$ black hole
- $M_{\rm Ch}$ is maximum white dwarf mass (the Chandrasekhar mass), and $M_{\rm NS}$ is the maximum neutron star mass:
    - $M_{\rm Ch} = 1.44\, M_{\odot}$
    - $M_{\rm NS}$ is much less certain:
        - $M_{\rm NS} \approx 1.5\, M_{\odot}$ (Brown & Bethe 1994)
        - $M_{\rm NS} = 2.16^{+0.17}_{-0.15}\, M_{\odot}$ (Rezzolla, Most, & Weih 2018)

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    - MSP J0740+6620 has $M = 2.14^{+0.10}_{-0.09}\, M_\odot$ (Cromartie et al. 2021)

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  - $M_{\rm NS}$ is much less certain:
    - $M_{\rm NS} \approx 5.76\, M_\odot$ (neutron degeneracy, Srinivasan 2002)
    - $M_{\rm NS} \approx 3.2\, M_\odot$ (causality, Rhoades & Ruffini 1974)
    - $M_{\rm NS} \approx 2.9\, M_\odot$ (EOS, Kalogera & Baym 1996)

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- $M_{\rm Ch}$ is maximum white dwarf mass (the Chandrasekhar mass), and $M_{\rm NS}$ is the maximum neutron star mass.
- Let's round $M_{\rm NS}$ to $3\,M_{\odot}$ and and define a black hole as a compact object with a mass larger than $3\,M_{\odot}$.

Number of (Stellar) Black Holes in the Milky Way

- *Single* stars above a certain initial mass threshold will produce black holes (threshold depends on metallicity).
- There is a certain level of chemical enrichment in the Milky Way (e.g. heavy elements), most of these elements need supernovae to be produced.
- There should be between $\approx 10^8$ and $\approx 10^9$ stellar black holes in the Milky Way (Agol & Kamionkowski 2002).

How to Detect (Stellar) Black Holes

- Isolated stellar black holes are expected to be small, massive, and dark. How to detect them?
- Detect signatures of accretion from the ISM (interstellar medium):
  - Zel'dovich and Salpeter, independently in the 1960s, Shvartsman (1971)
  - Agol & Kamionkowski (2002), Chisholm, Dodelson, & Kolb (2003)
  - These are not the brightest bulbs on the Christmas tree...

How to Detect (Stellar) Black Holes

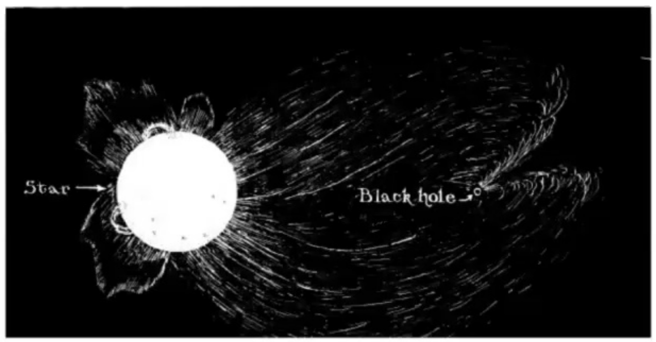
- Isolated stellar black holes are expected to be small, massive, and dark. How to detect them?
- Detect signatures of accretion from the ISM (interstellar medium).
- Detect massive and dark lensing objects in microlensing surveys:
  - Lens mass depends on the time-scale of lensing event, but you also need the lensing parallax to help reduce degeneracies.
  - OGLE-2006-BLG-044 has a 39% probability that the lens mass is $> 3\,M_\odot$ (Karolinski & Zhu 2020).

How to Detect (Stellar) Black Holes

- Can we find black holes in binary systems?
- Using optical observations, find single-lined spectroscopic binaries that seem to have a massive, and (optically) dark companion:
  - LB-1: $M_c = 68^{+11}_{-3}\,M_\odot$ (Liu et al. 2019)
  - 2MASS J05215658+4359220: $M_c = 3.3^{+2.8}_{-0.7}\,M_\odot$ (Thompson et al. 2019)
  - V723 Mon: $M_c = 3.04 \pm 0.06\,M_\odot$ (Jayasinghe et al. 2021)
  - Note these stars are giants with relatively large (optical) luminosities, this makes it harder to rule out main sequence companions.
  - LB-1 may not have a black hole (Abdul-Hasih et al. 2020), but the other two seem to be more likely.

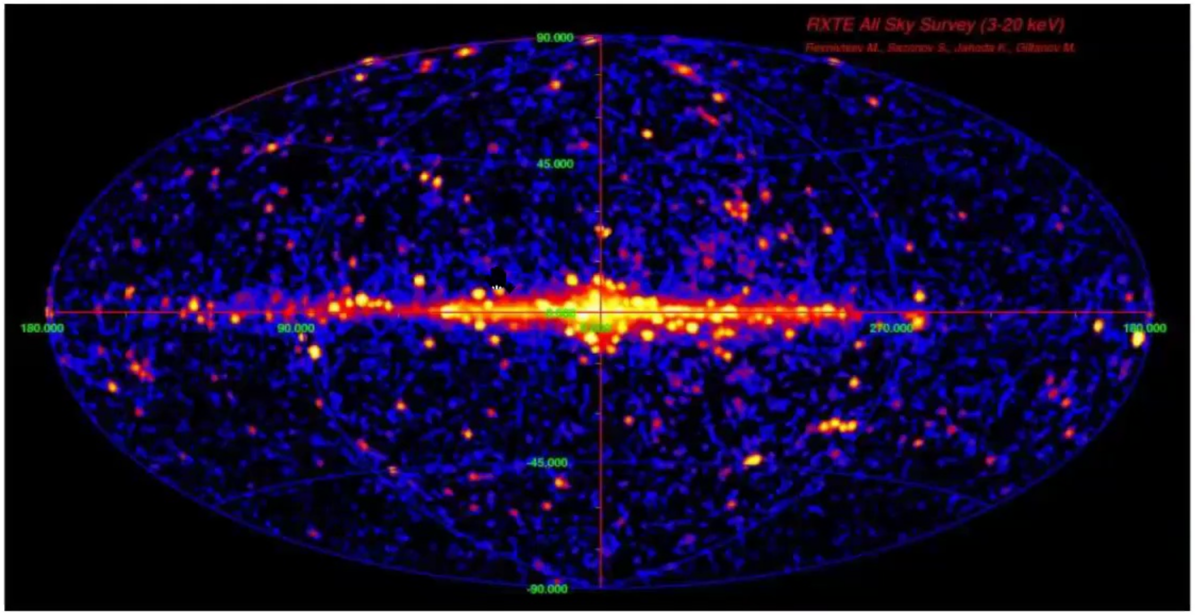
How to Detect (Stellar) Black Holes

- Can we find black holes in binary systems?
- Using optical observations, find single-lined spectroscopic binaries that seem to have a massive, and (optically) dark companion:
- In a close binary system, look for signs of accretion of matter from a "normal" star:
  - Zel'dovich & Novikov (1966), illustration from Thorne (1994)



8.5 The Zel'dovich-Novikov proposal of how to search for a black hole. A wind, blowing off the surface of a companion star, is captured by the hole's gravity. The wind's streams of gas swing around the hole in opposite directions and collide in a sharp shock front, where they are heated to millions of degrees temperature and emit X-rays. Optical telescopes should see the star orbiting around a heavy, dark companion. X-ray telescopes should see X-rays from the companion.

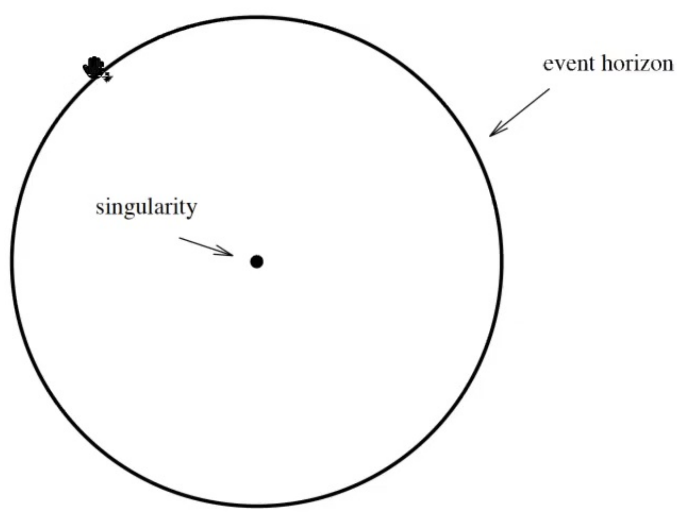
How to Detect (Stellar) Black Holes



- Rossi X-ray Timing Explorer all-sky X-ray map (Revnivtsev, Sazonov, & Gilfanov 1994)

What Black Hole Properties can we Measure?

- What properties can we measure?
  - Not many, just mass, angular momentum, and (in principle) electric charge.
  - Evidence for event horizons? See McClintock et al. (2003)



What Black Hole Properties can we Measure?

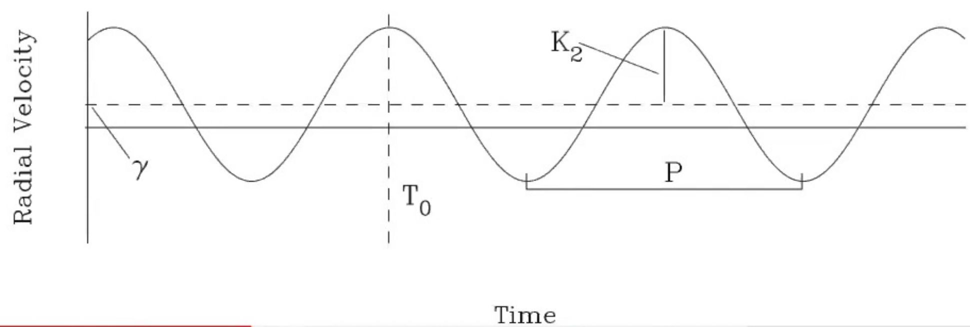
- How to measure the mass:
  - Circular orbit, separation a:

$$V_2 = \frac{2\pi a}{P}\left(\frac{M_1}{M_1 + M_2}\right) \quad (1)$$

  - Kepler's Third Law:

$$P^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)} \quad (2)$$

  - Define $K_2 = V_2 \sin i$, cube (1) and combine with (2):



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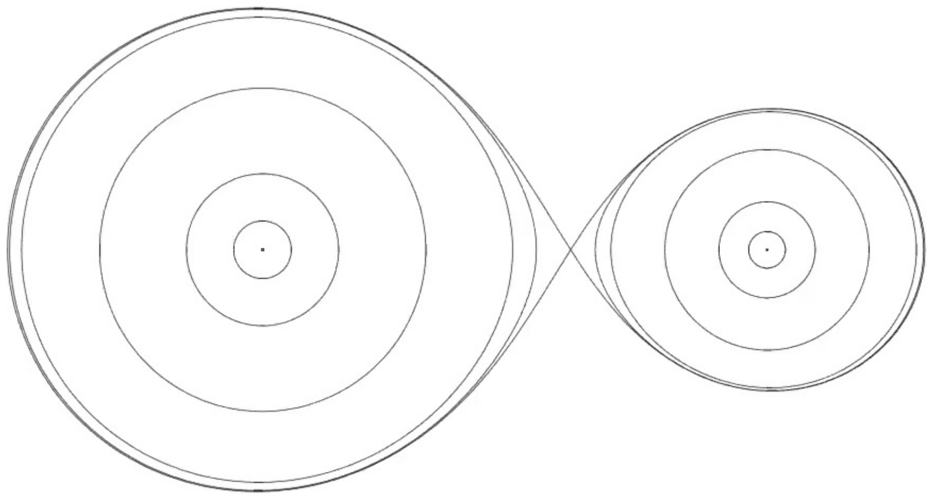
  - Define $q \equiv M_2/M_1$, then

$$f(M_1) = \frac{M_1^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{PK_2^3}{2\pi G} = \frac{M_1 \sin^3 i}{(1 + q)^2} \quad (4)$$

  - To find M_1 (the compact object mass), you need to find the inclination of the orbit i ($i = 90^\circ$ for edge-on), and either the mass ratio q, the optical star's mass M_2, or some constraint on the semimajor axis a.

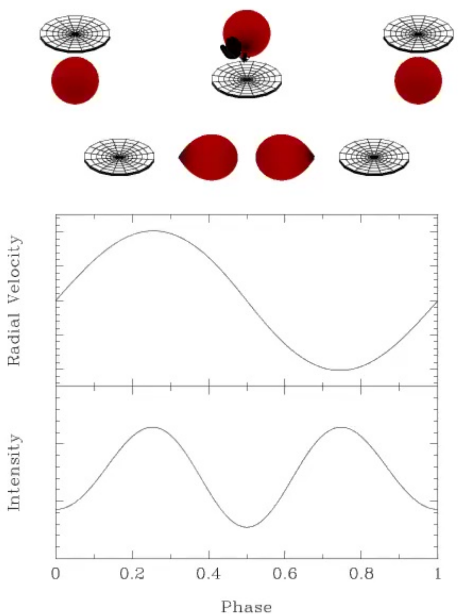
What Black Hole Properties can we Measure?

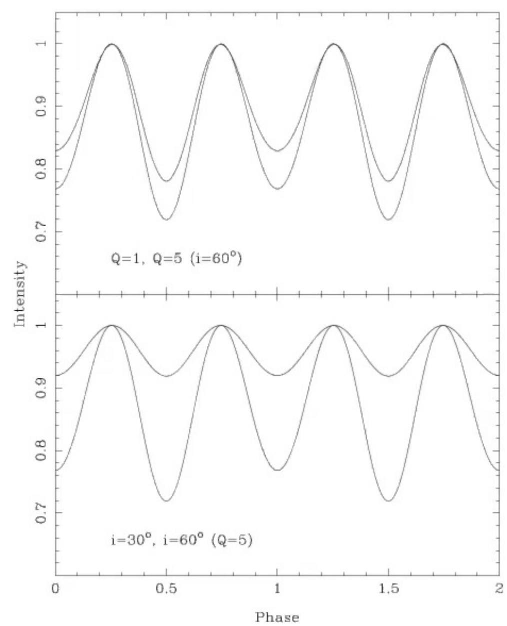
- How to measure the inclination:
  - The surface of a star should follow a gravitational equipotential, and in a close binary these equipotential surfaces may be distorted.
  - In a low mass X-ray binary, the companion star fills its Roche lobe and mass is transferred through the inner Lagrangian point.



What Black Hole Properties can we Measure?

- How to measure the inclination:
  - As the star moves in its orbit, the observer sees a variable projected area on the sky, hence the flux is modulated. These variations (called ellipsoidal variations) depend on *i* and *q*.





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- How to measure the inclination:
  - Note that in a high mass X-ray binary (the donor is an O-star or a B-star instead of a G-dwarf or K-dwarf), the mass transfer is via stellar winds, so the mapping between the ellipsoidal light curves and the inclination is more complicated.

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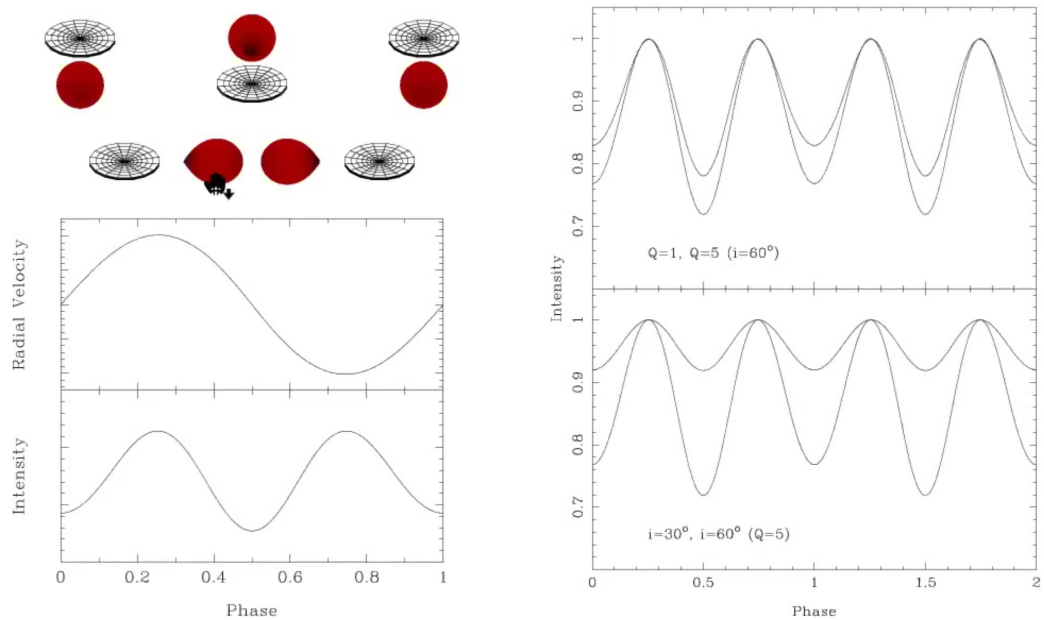

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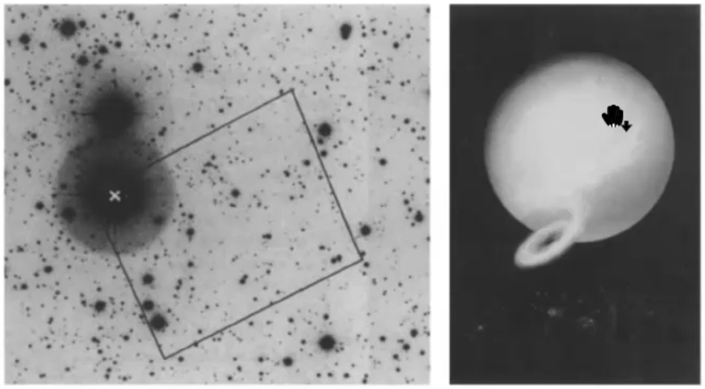
Discovery, Early History

- What about Cygnus X-1?
  - Discovered in a rocket flight in 1964 (Boyer et al. 1965).
  - *Uhuru* observations localized the source to a ≈ 2, arcminute square region in Cygnus.
  - A radio flare that was correlated with an X-ray flare enabled the X-ray source to be associated with an O-star with the designation HDE 226868 (Hjellming & Wade 1971; Bolton 1971).

Discovery, Early History



8.7 Left: **A negative print of a photograph taken with the 5-meter (200-inch) optical telescope at Palomar Mountain by Jerome Kristian in 1971. The black rectangle outlines the error box in which Uhuru's 1971 data say that Cygnus X-1 lies. The white x marks the location of a radio flare, measured by radio telescopes, which coincided with a sudden change in the X-rays from Cyg X-1. The x coincides with the optical star HOE 226868, and thus identifies it as a binary companion of Cyg X-1. In 1978 the X-ray telescope Einstein confirmed this identification; see Figure 8.6g.** ***Right:*** **Artist's conception of Cyg X-1 and HDE 226868, based on all the optical and X-ray data.** [Left: photo courtesy Dr. Jerome Kristian, Carnegie Observatories; right: painting by Victor J. Kelley, courtesy the National Geographic Society.]

- Illustration from Thorne (1994).

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  - HDE 226868 was subsequently discovered to be a single-lined spectroscopic binary with a period of 5.6 days, with an optical mass function of $0.217 \pm 0.007\,M_\odot$ (Bolton 1975).

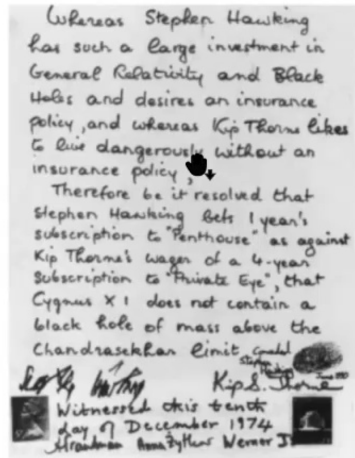
Why is it so Hard?

- We have the optical mass function of $f(M) = 0.240 \pm 0.005\, M_{\odot}$. Now all we need is the inclination of the orbit i and the mass of the O-star...

Why is it so Hard?

- We have the optical mass function of $f(M) = 0.240 \pm 0.005\, M_{\odot}$. Now all we need is the inclination of the orbit i and the mass of the O-star...
  - The X-ray source is wind-fed, so the inclination is not easily obtained from the ellipsoidal light curves.
  - The distance and reddening were uncertain, so the properties of the O-star were not well known? What is its mass? Is it a "normal" O-star or is it undermassive and underluminous?
- Some early mass estimates include
  - $M_1 < 1\, M_{\odot}$ (Trimble 1973)
  - $M_1 > 3.6\, M_{\odot}$ for $d > 1.4$ kpc (Paczynski 1974)
  - $M_1 > 7\, M_{\odot}$ (Gies & Bolton 1986)
  - $M_1 = 10 \pm 1\, M_{\odot}$ (Ninkov et al. 1987)

Why is it so Hard?



Whereas Stephen Hawking has such a large investment in General Relativity and Black Holes and desires an insurance policy, and whereas Kip Thorne likes to live dangerously without an insurance policy,

Therefore be it resolved that Stephen Hawking bets 1 year's subscription to "Penthouse" as against Kip Thorne's wager of a 4-year subscription to "Private Eye", that Cygnus X 1 does not contain a black hole of mass above the Chandrasekhar limit.

Kip S. Thorne

Witnessed this tenth day of December 1974

***Right:* The bet between Stephen Hawking and me as to whether Cygnus X-1 is a black hole. *Left:* Hawking lecturing at the University of Southern California in June 1990, just two hours before breaking into my office and signing off on our bet.** [Hawking photo courtesy Irene Fertik, University of Southern California.]

- In 1974, Stephan Hawking and Kip Thorne made a bet on whether Cygnus X-1 has a black hole, Hawking bet that it did not.
- Hawking conceded in 1990 (illustration from Thorne 1974).

2011 Results

- What changed in 2011?

2011 Results

THE ASTROPHYSICAL JOURNAL, 742:83 (5pp), 2011 December 1 doi:10.1088/0004-637X/742/2/83

THE TRIGONOMETRIC PARALLAX OF CYGNUS X-1

MARK J. REID[1], JEFFREY E. MCCLINTOCK[1], RAMESH NARAYAN[1], LIJUN GOU[1], RONALD A. REMILLARD[2], AND JEROME A. OROSZ[3]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[2] Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 70 Vassar Street, Cambridge, MA 02139, USA
[3] Department of Astronomy, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182, USA
Received 2011 June 17; accepted 2011 July 19; published 2011 November 9

ABSTRACT

We report a direct and accurate measurement of the distance to the X-ray binary Cygnus X-1, which contains the first black hole to be discovered. The distance of $1.86^{+0.12}_{-0.11}$ kpc was obtained from a trigonometric parallax measurement using the Very Long Baseline Array. The position measurements are also sensitive to the 5.6 day binary orbit and we determine the orbit to be clockwise on the sky. We also measured the proper motion of Cygnus X-1 which, when coupled to the distance and Doppler shift, gives the three-dimensional space motion of the system. When corrected for differential Galactic rotation, the non-circular (peculiar) motion of the binary is only about 21 km s^{-1}, indicating that the binary did not experience a large "kick" at formation.

Key words: astrometry – black hole physics – stars: distances – stars: individual (Cygnus X-1) – X-rays: binaries

Online-only material: color figures

- We got a parallax to the source using VLBI.

2011 Results

THE ASTROPHYSICAL JOURNAL, 742:83 (5pp), 2011 December 1 REID ET AL.

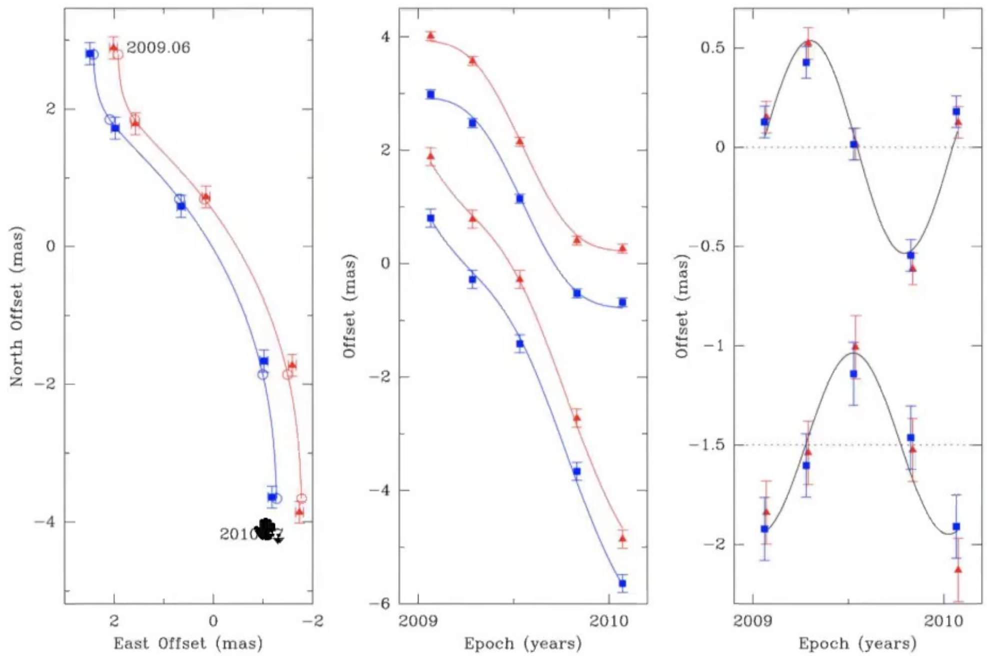


Figure 2. Parallax and proper motion data and fits. Plotted are position offsets of Cygnus X-1 relative to the two background sources: J1953+3537 (red triangles) and J1957+3338 (blue squares). The degree-scale separations of the absolute positions given in Table 1 have been removed. The yearly sinusoidal position variations (the parallax signature) caused apparent position shifts of Cygnus X-1 as the Earth orbits the Sun. Left panel: positions on the sky with first and last epochs labeled. Data for the two background source are offset horizontally for clarity. The expected positions from the parallax and proper motion fit are indicated (circles). Middle panel: east (top lines) and north (bottom lines) position offsets and best-fit parallax and proper motions vs. time. Data for the two background sources and two coordinates are offset vertically for clarity. Right panel: same as the middle panel, except the best-fit proper motions have been removed, allowing all data to be overlaid and the effects of only the parallax seen. The north offset data have been offset vertically (below) the east offset data for clarity.

2011 Results

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Key words: astrometry – black hole physics – stars: distances – stars: individual (Cygnus X-1) – X-rays: binaries

Online-only material: color figures

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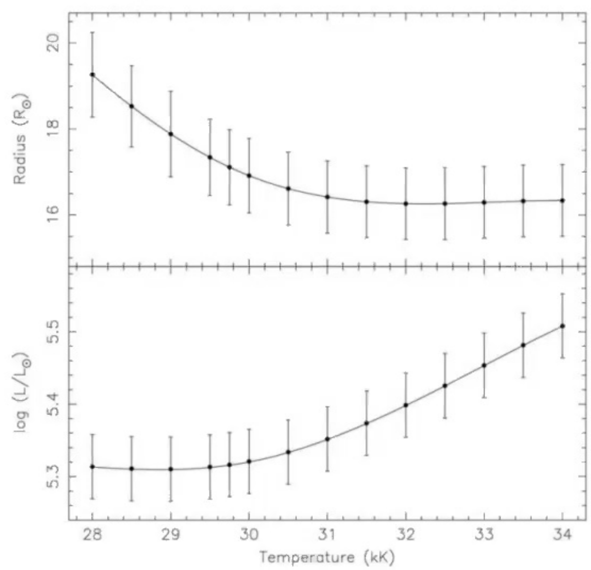
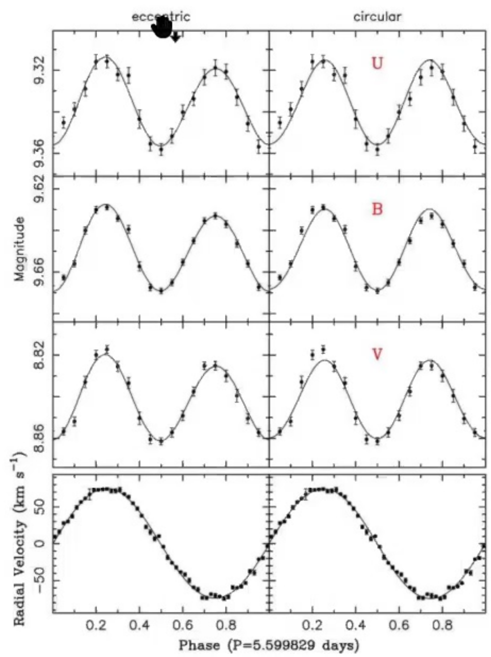
2011 Results

- What changed in 2011?
- We got a parallax to the source using VLBI.
- The steps to get the mass:
  - Using the apparent magnitude in K and the reddening, find the radius of the O-star as a function of effective temperature.
  - Model the light and radial velocity curves, using the stellar radius and the projected rotational velocity (from spectroscopy) as constraints.
  - As a function of temperature, fit 4 cases:
    - (A) circular orbit, synchronous rotation;
    - (B) circular orbit, nonsynchronous rotation;
    - (C) eccentric orbit, pseudosynchronous rotation;
    - (D) eccentric orbit, nonsynchronous rotation.

2011 Results





- Left: Radius and luminosity as a function of $T_{\rm eff}$;
- Right: Light and velocity curve fits for model D (left) and A (right).

2011 Results

The Astrophysical Journal, 742:84 (10pp), 2011 December 1 doi:10.1088/0004-637X/742/2/84

THE MASS OF THE BLACK HOLE IN CYGNUS X-1

Jerome A. Orosz[1], Jeffrey E. McClintock[2], Jason P. Aufdenberg[3], Ronald A. Remillard[4], Mark J. Reid[2], Ramesh Narayan[2], and Lijun Gou[2]
[1] Department of Astronomy, San Diego State University, San Diego, CA 92182-1221, USA; orosz@sciences.sdsu.edu
[2] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA; jem@cfa.harvard.edu, reid@cfa.harvard.edu, narayan@cfa.harvard.edu, lgou@cfa.harvard.edu
[3] Physical Sciences Department, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA; aufded93@erau.edu
[4] Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA; rr@space.mit.edu
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ABSTRACT

Cygnus X-1 is a binary star system that is comprised of a black hole and a massive giant companion star in a tight orbit. Building on our accurate distance measurement reported in the preceding paper, we first determine the radius of the companion star, thereby constraining the scale of the binary system. To obtain a full dynamical model of the binary, we use an extensive collection of optical photometric and spectroscopic data taken from the literature. By using all of the available observational constraints, we show that the orbit is slightly eccentric (both the radial velocity and photometric data independently confirm this result) and that the companion star rotates roughly 1.4 times its pseudosynchronous value. We find a black hole mass of $M = 14.8 \pm 1.0\,M_\odot$, a companion mass of $M_{\rm opt} = 19.2 \pm 1.9\,M_\odot$, and the angle of inclination of the orbital plane to our line of sight of $i = 27.1 \pm 0.8$ deg.

Key words: binaries: general – black hole physics – stars: individual (Cygnus X-1) – X-rays: binaries

- Final results, assuming $30,000\,\mathrm{K} \leq T_{\rm eff} \leq 32,000$ K.

2020 Updates

- Are we done yet? No? What happened?
  - *Gaia* DR2 and eDR3 results: optical parallax is $468 \pm 15 \mu\mathrm{as}$, compared to 539 ± 33 from VLBI (≈ 2.14 kpc vs. ≈ 1.86 kpc).
  - More VLBI observations over a single binary orbit.

2020 Updates

BLACK HOLES

Cygnus X-1 contains a 21–solar mass black hole—Implications for massive star winds

James C. A. Miller-Jones[1*], Arash Bahramian[1], Jerome A. Orosz[2], Ilya Mandel[3,4,5], Lijun Gou[6,7], Thomas J. Maccarone[8], Coenraad J. Neijssel[3,4,5], Xueshan Zhao[6,7], Janusz Ziółkowski[9], Mark J. Reid[10], Phil Uttley[11], Xueying Zheng[6,7]†, Do-Young Byun[12,13], Richard Dodson[14], Victoria Grinberg[15], Taehyun Jung[12,13], Jeong-Sook Kim[12], Benito Marcote[16], Sera Markoff[11,17], María J. Rioja[14,18,19], Anthony P. Rushton[20,21], David M. Russell[22], Gregory R. Sivakoff[23], Alexandra J. Tetarenko[24], Valeriu Tudose[25], Joern Wilms[26]

- Miller-Jones, et al. (2021), Science, 371, 1046.

2020 Updates

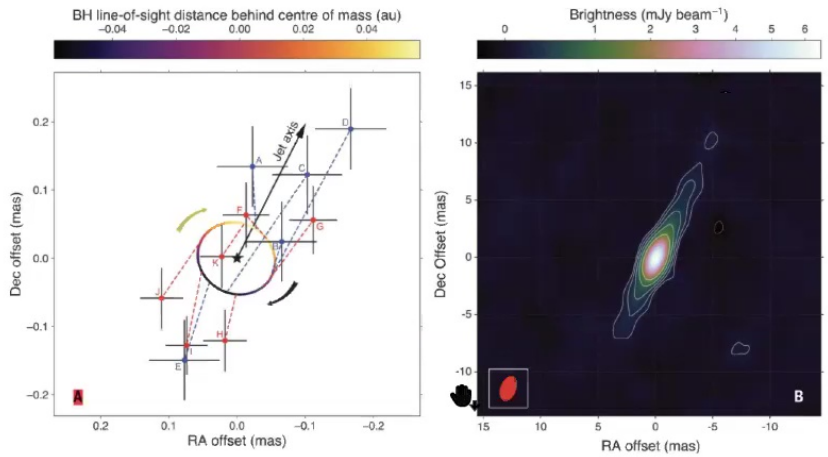

Fig. 1. Cygnus X-1 and its best fitting model orbit on the plane of the sky. (**A**) Astrometric measurements from the new (red points) and archival (blue points) VLBA data (*5*). Error bars show the 68% confidence level. The letter labels indicate the chronological ordering of the observations, as detailed in table S1. Dashed lines link the measured positions to the location on the fitted orbit, shown as the colored ellipse. The color bar indicates the location of the black hole along the line of sight, relative to the center of mass of the system (shown as the black star), with positive values being behind the center of mass. Arrows indicate the direction of orbital motion and the jet axis. (**B**) Stacked radio image of the jet in color, with white contours every $\pm(\sqrt{2})$ times the root mean square noise level of 23 microjanskys (μJy) per beam. The red ellipse indicates the size and shape of the synthesized beam. Although the measured positions scatter along the jet axis, the motion perpendicular to the jet axis is reproduced by the astrometric model (Fig. 2). Coordinates are given in right ascension (RA) and declination (Dec), J2000 equinox. mas, milli–arc seconds.

- Astrometric measurements show an orbital phase dependence, attributed to free-free absorption in the stellar wind. To mitigate, fit positions in the perpendicular direction of the known jet axis.

2020 Updates

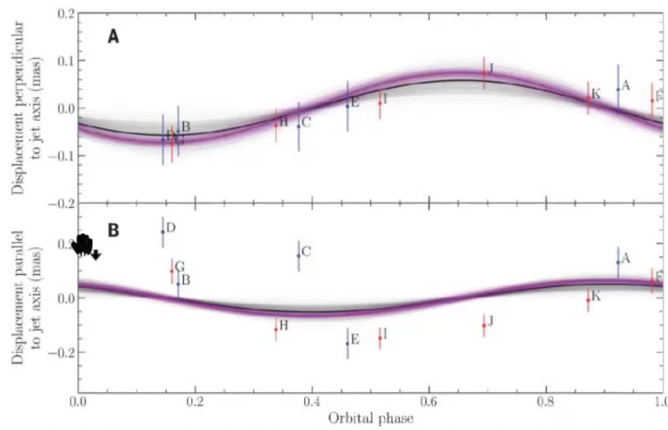

Fig. 2. Orbital displacements relative to the best-fitting one-dimensional astrometric model. Parallax and proper motion signatures have been subtracted. (**A**) The measured displacements perpendicular to the jet axis. Red points are our VLBA data, and blue points are the archival observations (*5*), with error bars showing the 68% confidence level. Labels reflect the chronological ordering of the observations, as listed in table S1. Black and magenta lines show 500 random draws from the posterior probability distribution of the orbital parameters for radio and optical models, respectively (with the posterior medians indicated with thicker lines), which are consistent within the uncertainties. The data were only fitted perpendicular to the jet axis. (**B**) The measured displacements parallel to the jet axis show that the measured core positions are primarily downstream of the model predictions when the black hole is close to superior conjunction (behind the donor star; phases close to 0.0) and upstream when the black hole is close to inferior conjunction (phases close to 0.5), as expected for wind absorption.

- Astrometric measurements show an orbital phase dependence, attributed to free-free absorption in the stellar wind. To mitigate, fit positions in the perpendicular direction of the known jet axis.

2020 Updates

- We find a parallax of $458 \pm 35\,\mu\mathrm{as}$, compared to $468 \pm 15\,\mu\mathrm{as}$ from *Gaia* eDR3.
- Now update the dynamical model:
    - Adopt $d = 2.22 \pm 0.18$ kpc, get new $R_1(T_{\mathrm{eff}})$ relation.
    - Adopt $T_{\mathrm{eff}} = 30,200 \pm 900$ K and a gravity of $\log g_1 = 3.31 \pm 0.05$.
    - Adopt $V_{\mathrm{rot}} \sin i = 96 \pm 6$ km s^{-1}.
    - Use MCMC fitting, assuming the model D framework.

2020 Updates

- We find a parallax of $458 \pm 35\,\mu\mathrm{as}$, compared to $468 \pm 15\,\mu\mathrm{as}$ from *Gaia* eDR3.
- Now update the dynamical model:
  - We find $M = 21.2 \pm 2.2\,M_\odot$ for the black hole and $M_2 = 40.6 \pm 7.7\,M_\odot$ for the O-star, respectively.
  - $R_2 = 22.3 \pm 1.8\,R_\odot$ and $\log(L_2/L_\odot) = 5.63 \pm 0.08$.
  - $a_{\mathrm{BH}} = 0.160 \pm 0.013$ au or $73 \pm 8\,\mu\mathrm{as}$ for the apparent semimajor axis of the black hole orbit. The VLBI fit gives $58 \pm 20\,\mu\mathrm{as}$.

2020 Updates

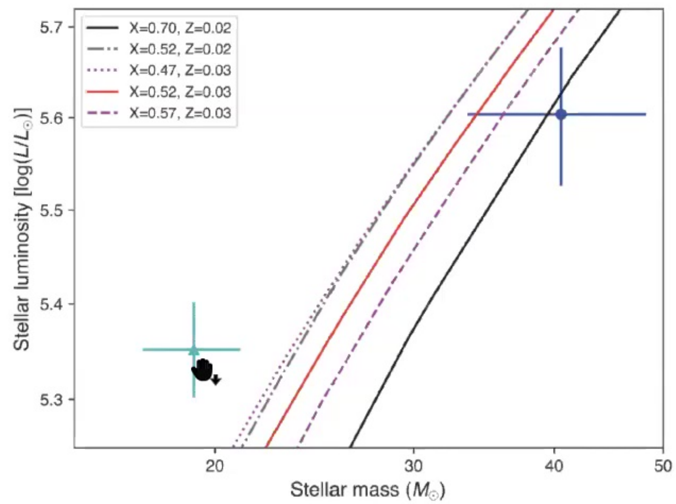

Fig. 3. Predicted mass-luminosity relations for high-mass main sequence stars. Masses are given in solar masses, and luminosities are relative to the solar luminosity $L_{\odot}$. The black solid line shows the predicted relation for a standard composition [hydrogen mass fraction $X = 0.70$; mass fraction of heavy elements $Z = 0.02$ (*10*)]. The gray dot-dashed line is for an enhanced helium abundance, $X = 0.52$, $Z = 0.02$ [as inferred for the surface abundance of the donor star (*15*)]. The red solid line shows the effect of an increased metallicity, with $Z = 0.03$, $X = 0.52$. The magenta dotted line and dashed line show the effect of the uncertainty on the helium abundance (*15*). The mass and luminosity determined from previous observations (*6*) are shown as the cyan triangle. The values derived from our observations are shown as the blue circle, which lies closer to the theoretical relations, irrespective of composition or metallicity. Error bars show 68% confidence levels.

- The O-star parameters are more consistent with evolutionary models.

Implications for Black Hole Spin

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Re-estimating the Spin Parameter of the Black Hole in Cygnus X-1

Xueshan Zhao[1,2], Lijun Gou[1,2], Yanting Dong[1,2], Xueying Zheng[1,2], James F. Steiner[3], James C. A. Miller-Jones[4], Arash Bahramian[4], Jerome A. Orosz[5], and Ye Feng[1,2]

[1] Key Laboratory for Computational Astrophysics, National Astronomical Observatories, Chinese Academy of Sciences, Datun Road A20, Beijing 100012, People's Republic of China; xszhao@nao.cas.cn, lgou@nao.cas.cn
[2] School of Astronomy and Space Sciences, University of Chinese Academy of Sciences, Datun Road A20, Beijing 100049, People's Republic of China
[3] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[4] International Centre for Radio Astronomy Research—Curtin University, GPO Box U1987, Perth, WA 6845, Australia
[5] Astronomy Department, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182-1221, USA
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Abstract

Cygnus X-1 is a well-studied persistent black hole X-ray binary. Recently, the three parameters needed to estimate the black hole spin of this system, namely the black hole mass M, the orbital inclination i, and the source distance D, have been updated. In this work we redetermine the spin parameter using the continuum-fitting technique for those updated parameter values. Based on the assumption that the spin axis of the black hole is aligned with the orbital plane, we fit the thermal disk component to a fully relativistic thin accretion disk model. The error in the spin estimate arising from the combined observational uncertainties is obtained via Monte Carlo simulations. We demonstrate that, without considering the counteracting torque effect, the new spin parameter is constrained to be $a_* > 0.9985$ (3σ), which confirms that the spin of the black hole in Cygnus X-1 is extreme.

Unified Astronomy Thesaurus concepts: X-ray binary stars (1811); Black hole physics (159); High energy astrophysics (739)

Implications for Black Hole Spin

- The radius of the horizon is a function of the BH mass and spin:

$$r_h = r_g + (r_g^2 - a^2)^{1/2} = r_g[1 + (1 - a_*^2)^{1/2}]$$

where

$$r_g = GM/c^2; \quad a = J/Mc; \quad a_* = a/r_g \quad (-1 \leq a_* \leq 1)$$

- The radius of the ISCO is a function of the BH mass and spin:

$$r_{\rm last} = r_g\{3 + A_2 \pm [(3 - A_1)(3 + A_1 + 2A_2)]^{1/2}\}$$

where

$$\begin{aligned} A_1 &= 1 + (1 - a_*^2)^{1/3}[(1 + a_*)^{1/3} + (1 - a_*)^{1/3}] \\ A_2 &= (3a_*^2 + A_1^2)^{1/2} \end{aligned}$$

Implications for Black Hole Spin

- The radius of the ISCO is a function of the BH mass and spin:

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- Note:

$$\begin{aligned} r_{\rm S} &= 2r_g \quad \text{Schwarzschild radius} \\ r_{\rm last} &= r_g \quad a_* = 1 \text{ (extreme prograde)} \\ r_{\rm last} &= 6r_g \quad a_* = 0 \text{ (static)} \\ r_{\rm last} &= 9r_g \quad a_* = -1 \text{ (extreme retrograde)} \end{aligned}$$

- Measure M and $r_{\rm last}$ and you can solve for a_*

Implications for Black Hole Spin

- Measure M and $r_{\rm last}$ and you can solve for a_*
  - Measure the angular size of the central accretion disk "hole" using X-ray continuum models.
  - Use the distance d, the inclination i (assume spin axis is parallel to orbital angular momentum), and the black hole mass M_1 to get $r_{\rm last}$ in physical units.
  - $a_* > 0.9985\,(3\sigma)$. The black holes found by LIGO, with the exception of GW190412, tend to have low spins.

Implications for the Formation

- The presence of a 21 $M_{\odot}$ black hole in a system with solar or supersolar metallicity had implications for mass loss in massive stars:
  - Mass loss in the Wolf-Rayet state is probably ≈ 3 times smaller than "standard" assumptions.
  - Mass loss in luminous blue variable winds is likewise ≈ 3 times smaller than "standard" assumptions.
  - With more retained mass, there could be reduced enrichment of the ISM.

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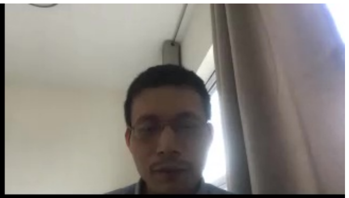

Questions?