3C273: a Supermassive Black Hole at the Edge of the Universe

Introduction

3C273 is a radio source with precise position first measured by lunar occultation[1]. It is the 273rd source in the Third Cambridge Catalog of Radio Sources ("3C"). In 1963, astronomers identified spectral lines in the optical spectrum but found that they are shifted by a large amount, unlike any stars seen before. It was called a quasi-stellar-object (QSO), or a quasar for short. We now know that quasars are supermassive black holes powered by accretion and they have very large distance.

Activity 1: Distance to the Andromeda galaxy M31

To have an idea of distance scales of galaxies, let's look at our neighbor, the Andromeda galaxy (M31), which has an apparent size of 3 degree in the sky.

1. Assuming that it has the same diameter as our Milky Way Galaxy, i.e. 10^5 light years, what is its distance in units of Mpc?

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2. Use Hubble's law, $v = H_0 d$, where H_0=68km/s/Mpc is the Hubble constant, to find the receding speed of M31.What redshift does this correspond to?

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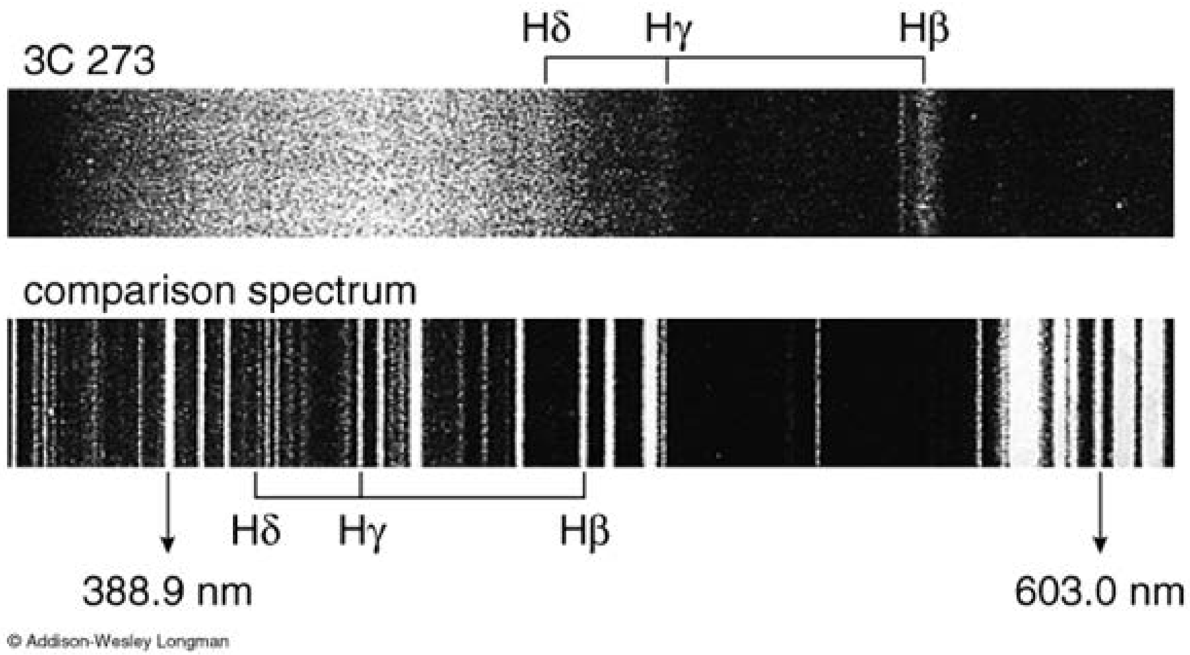
Activity 2: How Far is 3C273?

The image below shows the optical spectrum of 3C273 (top panel) compared with the reference spectrum at the lab frame (bottom panel). Three hydrogen lines (Hβ, Hγ, and Hδ) are detected.

[1] http://www.parkes.atnf.csiro.au/people/sar049/3C273/



1. By using a ruler to measure the image, determine the plate scale (nm/mm) of the spectrum.

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2. Measure the rest wavelengths of Hβ, Hγ, and Hδ in the reference spectrum

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3. What are the wavelengths of Hβ, Hγ, and Hδ in 3C273?

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4. Hence, determine the redshift of 3C273. What velocity is it moving?

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5. Use Hubble's law to determine the distance to 3C273.How far is it compared to M31?

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6. What do we see from the telescope is the view of 3C273 long time ago. When was the light from the source emitted?

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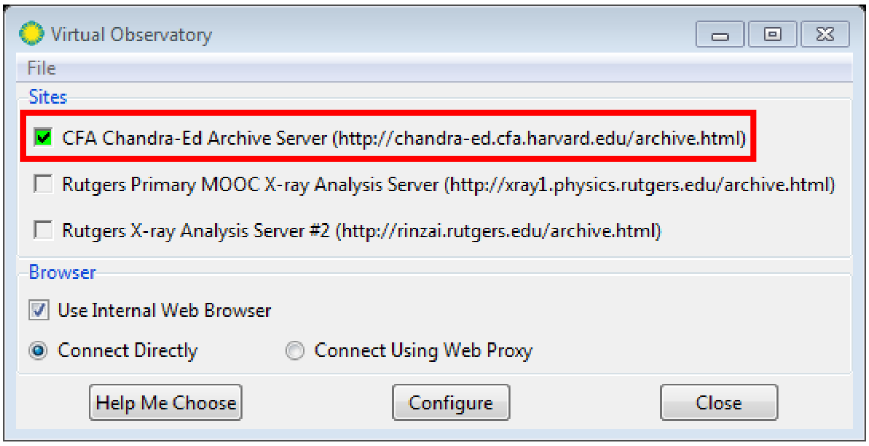
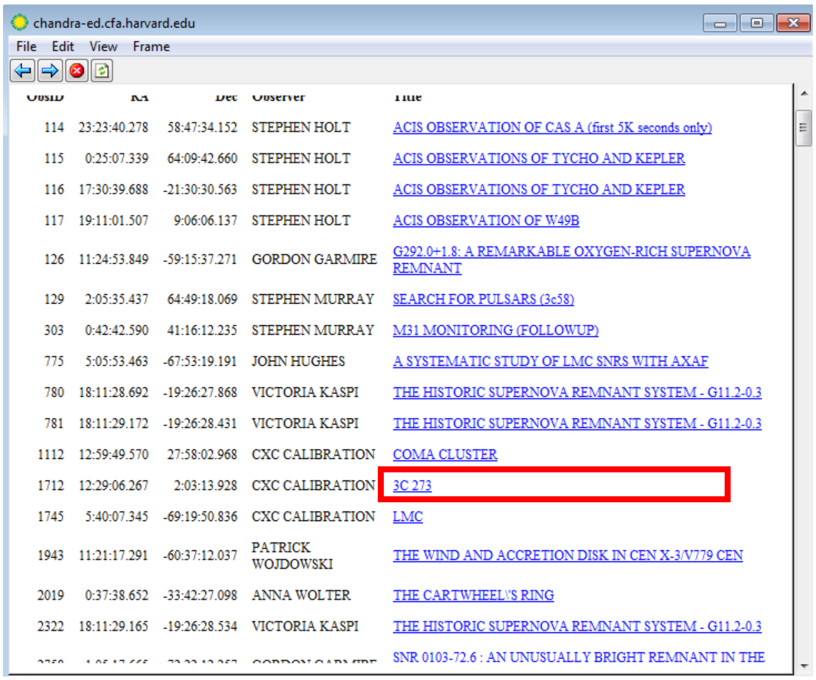
Activity 3: Luminosity of 3C273

From the exercise above, we learned that quasars are formed in the early Universe and they are located near the edge of the Universe. Given their large distance, they must be exceptionally bright. We will estimate the luminosity from an X-ray observation.

Start ***DS9***, go to ***Analysis-->Virtual Observatory***, connect to the ***CFA Server***, and select the ***3C273*** image.





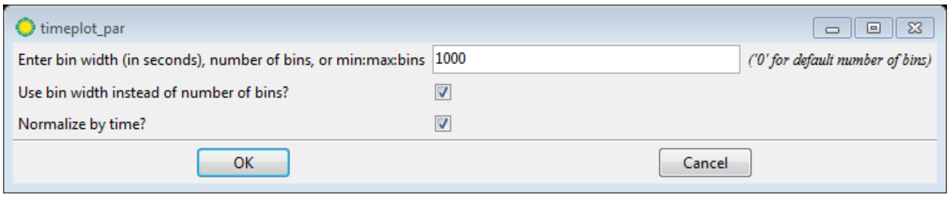
ObsID	RA	Dec	Observer	Title
114	23:23:40.278	58:47:34.152	STEPHEN HOLT	ACIS OBSERVATION OF CAS A (first 5K seconds only)
115	0:25:07.339	64:09:42.660	STEPHEN HOLT	ACIS OBSERVATIONS OF TYCHO AND KEPLER
116	17:30:39.688	-21:30:30.563	STEPHEN HOLT	ACIS OBSERVATIONS OF TYCHO AND KEPLER
117	19:11:01.507	9:06:06.137	STEPHEN HOLT	ACIS OBSERVATION OF W49B
126	11:24:53.849	-59:15:37.271	GORDON GARMIRE	G292.0+1.8: A REMARKABLE OXYGEN-RICH SUPERNOVA REMNANT
129	2:05:35.437	64:49:18.069	STEPHEN MURRAY	SEARCH FOR PULSARS (3c58)
303	0:42:42.590	41:16:12.235	STEPHEN MURRAY	M31 MONITORING (FOLLOWUP)
775	5:05:53.463	-67:53:19.191	JOHN HUGHES	A SYSTEMATIC STUDY OF LMC SNRS WITH AXAF
780	18:11:28.692	-19:26:27.868	VICTORIA KASPI	THE HISTORIC SUPERNOVA REMNANT SYSTEM - G11.2-0.3
781	18:11:29.172	-19:26:28.431	VICTORIA KASPI	THE HISTORIC SUPERNOVA REMNANT SYSTEM - G11.2-0.3
1112	12:59:49.570	27:58:02.968	CXC CALIBRATION	COMA CLUSTER
1712	12:29:06.267	2:03:13.928	CXC CALIBRATION	3C 273
1745	5:40:07.345	-69:19:50.836	CXC CALIBRATION	LMC
1943	11:21:17.291	-60:37:12.037	PATRICK WOJDOWSKI	THE WIND AND ACCRETION DISK IN CEN X-3/V779 CEN
2019	0:37:38.652	-33:42:27.098	ANNA WOLTER	THE CARTWHEEL'S RING
2322	18:11:29.165	-19:26:28.534	VICTORIA KASPI	THE HISTORIC SUPERNOVA REMNANT SYSTEM - G11.2-0.3
[illegible]	[illegible]	[illegible]	[illegible]	SNR 0103-72.6 : AN UNUSUALLY BRIGHT REMNANT IN THE

Under the ***Scale*** menu, Select "***log***". Right click and drag on the image to adjust the color scale.

Show the image here either by ***Export → JPEG*** in the menu or by screen capture.

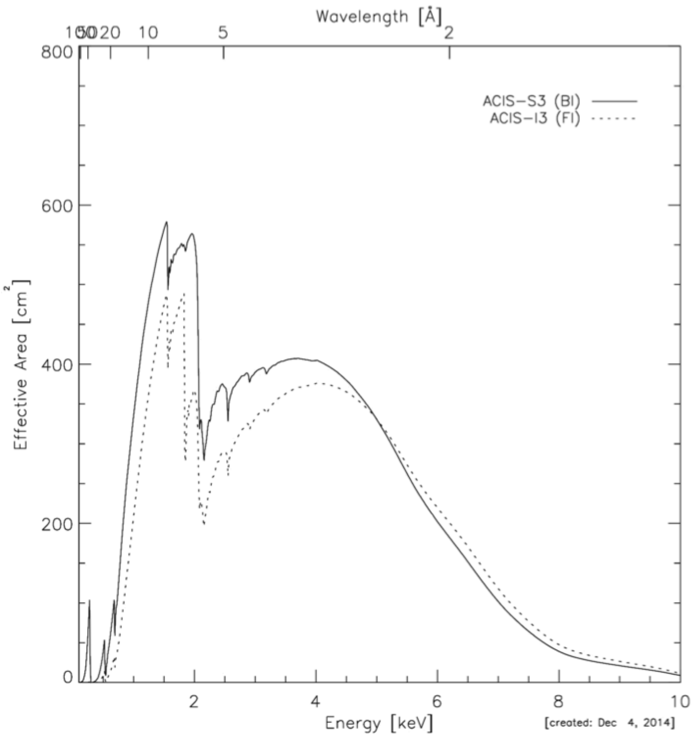
In the image, 3C273 appears like a disk with some black pixels at the centre. Note that this is **NOT** the actual size of the object (see the next activity) but just X-ray photons "spill over" to adjacent pixels because the source is very bright. For the same reason, the central pixels are saturated and appear as dark in the image. The long straight line across the image is another artifact, caused by the spread of photons along a column of the detector, as the source is too bright. You should see a jet pointing towards lower right, which is a real structure.

1. Draw a circular region to enclose**3C273** and its jet. Go to ***Analysis-->Chandra-Ed Analysis Tools-->Quick Light Curve Plot***, enter 1000 in the box and check both boxes below.



What is the count rate?

2. If we assume all photons are at 2keV, where the telescope sensitivity peaks, what is the energy flux of 3C273 in units of erg/s/cm^2? You may refer to the effective area of *Chandra* below (see the solid curve).



3. What is the power output of 3C273? How is it compared to the power of a galaxy? (You may assume ~10^{11} stars in the Milky Way Galaxy and all stars are Sun-like.

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4. In astrophysics there is a limit on how large the luminosity of a stable object can be. This is called the Eddington luminosity, given by

$$L_{\mathrm{Edd}} = 3.2 \times 10^4 \left(\frac{M}{M_\odot}\right) L_\odot.$$

Beyond that, the radiation pressure would exceed the gravitational force and the object will become unstable. Use this relation to set a lower limit on the mass of 3C273.

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Activity 4: How Big is 3C273?

1. 3C273 is known to show strong flux variability on different timescales, as short as 1.5 days. Suppose every part of the object brightened at once. We should first see the increased light from the close end then later from the furthest end, because light from the furthest end takes longer to reach the Earth. The delay is related to the light travel time across the object. Hence, we can estimate the size limit of the source. Using 1.5 days above, what is the maximum size of 3C273 compared with the Solar system?

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2. What is the angular diameter of 3C273 in arcseconds? Can it be resolved with Chandra? (Note that Chandra is the highest resolution X-ray telescope that human has ever built. It has a resolution of 2” and each pixel in the image corresponds to 0.5”.)

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3. For the jet, zoom in and measure the length by choosing ***Region→Shape→Line*** in the menu. Draw a line and double click it. An information windows should show up. What is the length in units of arcseconds?

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4. What is the physical size of the jet? Compare the result with the size of the Milky Way Galaxy (10^5 light years).

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Activity 5: Energy Source of 3C273

More detailed studies revealed that the mass of 3C273 is nearly $10^9 M_\odot$. Given the large mass and small size, the quasar 3C273 must be a black hole and the strong radiation is powered by accretion. To estimate the energy release when matter falls into a black hole, we first estimate the Schwarzschild radius. This is also known as the event horizon, inside which nothing can escape.

1. The Schwarzschild radius is given by $R_s = 2GM/c^2$. Estimate R_s for 3C273 and give the result in units of A.U.

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2. When a particle of mass *m* falls from infinity to the event horizon, what is the release in gravitational energy? If 50% of the energy can escape as radiation, what is the energy compared with the rest mass of the particle?

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This is much higher than 0.7% for nuclear fusion. Indeed, accretion is one of the most efficient process in the Universe.

3. When matter falls into a black hole, an accretion disk is formed due to conservation of angular momentum. The intense frictional heating in the disk gives rise to very high temperature. This makes 3C273 a strong X-ray source. We can have a simple estimate

of the temperature from the X-ray spectrum. Go to ***Analysis-->Chandra-Ed Analysis Tools-->Quick Energy Spectrum Plot from .1-10 kev*** to generate a spectrum.

Show the spectrum here.

At what energy does the spectrum peak? Convert this to Hz, then use Wien's displacement law, $\nu_{\max} = 5.88 \times 10^{10} T$ Hz, to estimate the temperature of 3C273. (Note that this is just a very rough estimate. A more detailed analysis should account for interstellar absorption and the source spectrum may not be a blackbody.)

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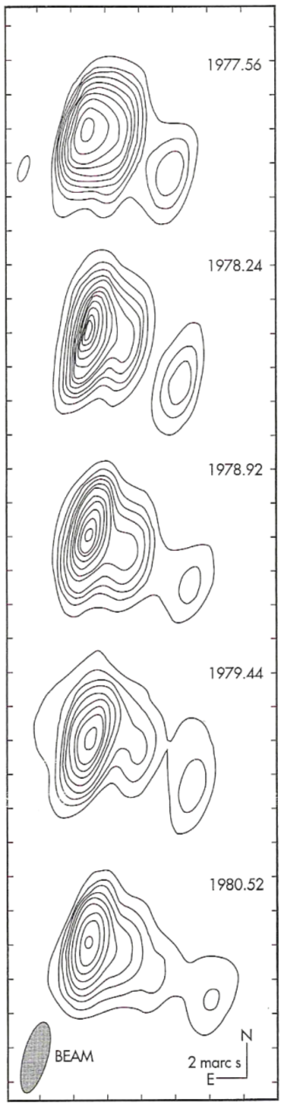
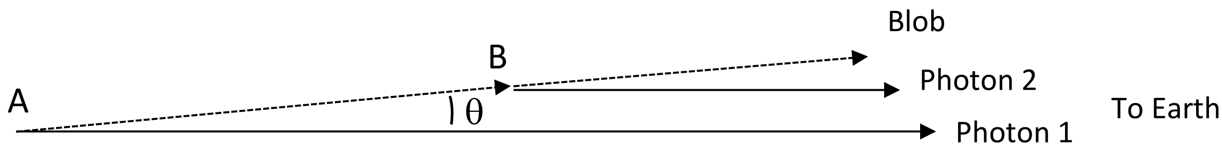
Activity 6: Faster than the Speed of Light?

1. The radio image on the right shows the evolution of a blob in the jet of 3C273. Use a ruler to measure the displacement relative to the quasar centre. Each tick mark represents 0.002 arcseconds. The numbers indicate the observation time in year. Convert the displacement from arcseconds to physical units and plot it below.



2. Determine the average speed of the jet in km/s. Compare the result with the speed of light.

3. This result appears to violate basic laws of physics, but it can be explained by the figure below. Suppose the blob moves at a small angle θ along the line of sight with speed v. It emitted photon 1 at A. After some time Δt, the blob travelled to position B and emitted photon 2.



(a) What is the difference between the arrival times of photons 1 and 2?

(b) What is the transverse displacement of the blob as seen on Earth?

(c) Hence, show that the apparent transverse speed is

$$v_{\text{app}}^{\text{T}} = \frac{v\ \sin\theta}{1 - \frac{v}{c}\cos\theta}\ .$$

(d) At what θ, $v_{\text{app}}^{\text{T}}$ attains the maximum? What is the maximum value of $v_{\text{app}}^{\text{T}}$? (Express all your answers in terms of v.)

(e) Use the result above and the apparent velocity measured from the radio image to estimate the minimum space velocity of the blob.