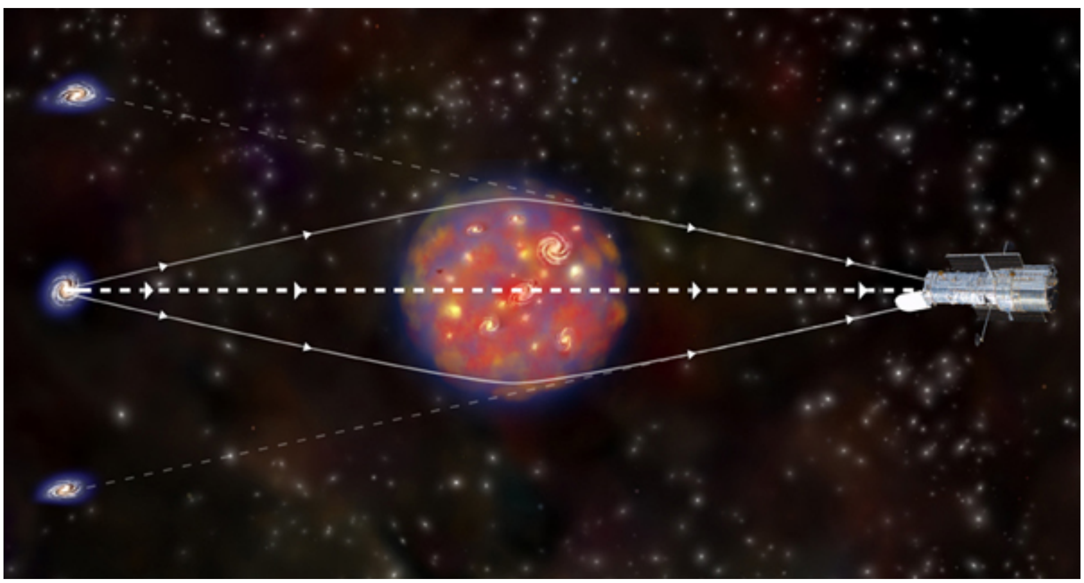
The Bullet Cluster – a js9 activity

Purpose: To examine the Bullet Cluster, 1E 0657-56, in various bands of the electromagnetic spectrum for evidence of dark matter.

Background:

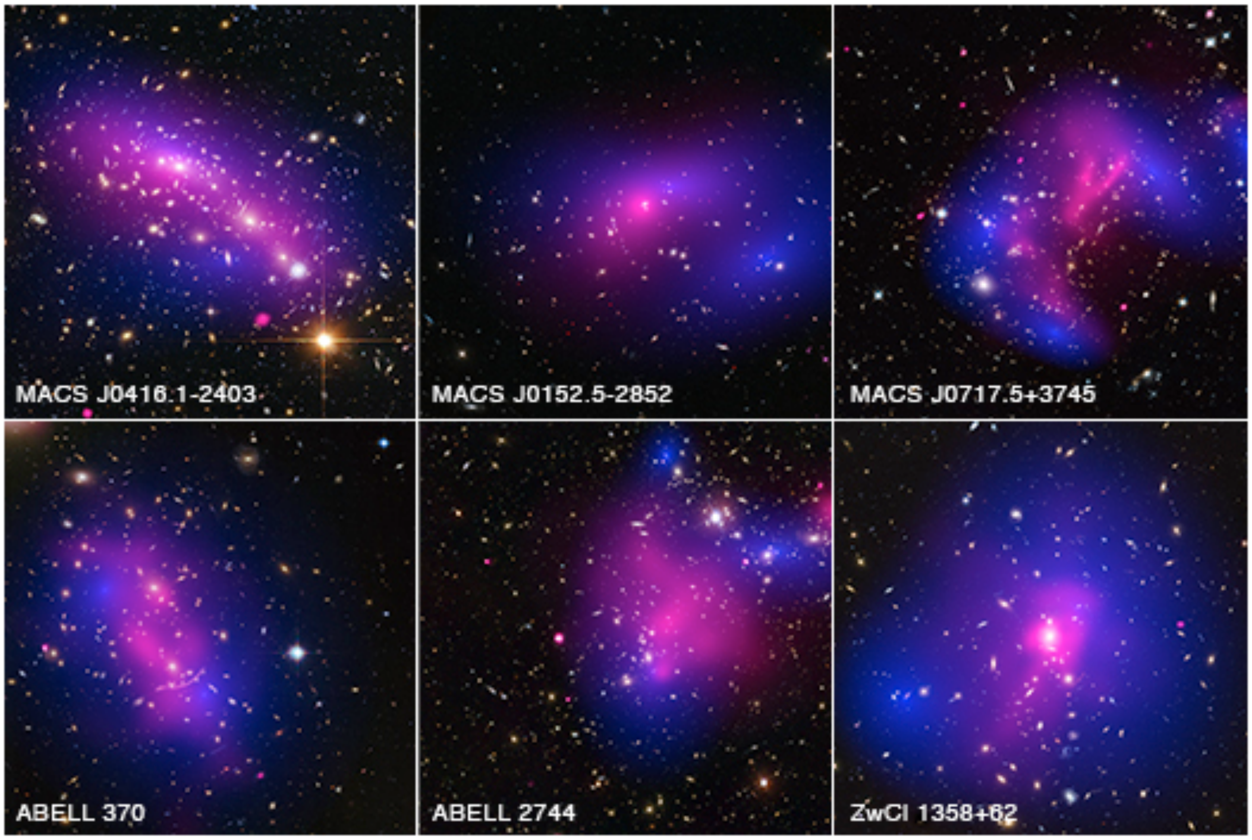
Dark matter is an invisible matter that makes up most of the mass of the universe. Because dark matter does not reflect, absorb or emit light, it can only be traced indirectly by, for example, measuring how it warps space through gravitational lensing.

According to Einstein's theory of general relativity, space is curved in the vicinity of strong gravitational fields. One consequence of the warping of space by gravity is that the path of light from background galaxies is bent when it passes near a cluster, in much the same way that a glass lens will bend light. The images of the galaxies are distorted by this "gravitational lensing" effect, by an amount that depends on the mass of the cluster. This method gives estimates for the amount of dark matter in galaxy clusters that is in good agreement with X-ray observations.



Strong gravitational lensing: Bending of light from background galaxies by a Massive galaxy cluster can be used to estimate the mass of the cluster. (Illustration: NASA/CXC/M.Weiss)

Galaxy clusters are made of three main ingredients: galaxies, gas clouds, and dark matter. During collisions, the gas clouds surrounding galaxies crash into each other and slow down or stop. The galaxies are much less affected by the drag from the gas and, because of the huge gaps between the stars within them, do not slow each other down. Using observations from NASA's Hubble Space Telescope and Chandra X-ray Observatory, astronomers found that, like the galaxies, the dark matter continued straight through the violent collisions without slowing down. This means dark matter does not interact with visible particles and flies by other dark matter with much less interaction than previously thought. Had the dark matter dragged against other dark matter, the distribution of galaxies would have shifted.



Credit: X-ray: NASA/CXC/Ecole Polytechnique Federale de Lausanne, Switzerland/D.Harvey & NASA/CXC/Durham Univ/R.Massey; Optical & Lensing Map: NASA, ESA, D. Harvey (Ecole Polytechnique Federale de Lausanne, Switzerland) and R. Massey (Durham University, UK)

Because the clouds of gas are very hot — millions of degrees — they glow brightly in X-ray light (pink in the image above). When combined with visible-light images from Hubble, the team was able to map the post-collision distribution of stars and also of the dark matter (blue in the image above). Astronomers can map the distribution of dark matter by analyzing how the light from distant sources beyond the cluster is magnified and distorted by gravitational lensing.

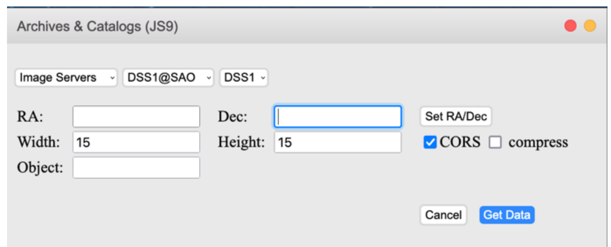
In this activity we will be examining the Bullet Cluster, 1E 0657-56, which was formed after a collision that was the most energetic event known in the universe since the Big Bang.

Procedure:

1. Go to https://chandra.si.edu/js9/ and go to **File>close>this image** in the js9 window to the left.

2. Go to https://chandra.harvard.edu/photo/2006/1e0657/ and scroll down to **Fast Facts for 1E 0657-56**. You will need the right ascension (RA) and declination (dec) for the next step.

3. In js9, go to **View>Archives & Catalogs**. The default server is **DSS1@SAO, DSS1**. This will retrieve the optical data. Put in the RA and dec from the Fast Facts. Degrees, hours and minutes should be separated by semi colons. For example, 06h 58m 37.9s should be entered as 06:58:37.9. Click "Get Data."



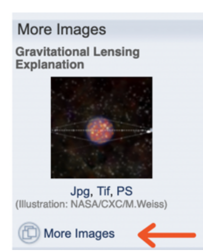
RA = _____ **:** _____ **:** _____ **Dec =** _____ **:** _____ **:** _____

4. To retrieve the x-ray data, click the **"Unofficial Chandra Archive Search Page"** button. In the window that comes up, enter "Bullet Cluster" or "1E 0657-56" where it says "object name" and then "Search."

5. In the results that come up, drag the link under "Title" for the observation with the longest exposure time into the js9 window. Choose **Scale>log**.

6. With the x-ray image still showing in the js9 window, line up the x-ray and optical image. Go to **wcs>wcs reproject** and click the name of the DSS1 FITS file (optical) and then "open." Choose **Zoom>zoom2** to get a close up of the x-ray data.

7. Go back to the Bullet Cluster page in the Chandra Photo Album (link is in step #2). To the right, under where it says "More Images" click the link "more images" under the picture "Gravitation Lensing Explanation."



8. On the page that comes up, you should see an image labeled "Optical/Lensing Map." Click this link and you should see the image. Right click the image and save this to your desktop.

Optical/Lensing Map
Jpeg, Tif, PS

9. In js9, go to **File>open local** and browse on your computer for the optical/lensing image you saved in step #8. If you did not rename it, it should be called *1e0657_opt_lens.jpg*.

10. Again, go back to the Fast Facts section of the Bullet Cluster page in the Chandra Photo Album (link in step #2). Find the scale of the image. When js9 loads an image, it fits it so the height fills the window. This is the second number of the scale. Convert this from arc min to arc sec. **height _____ arc min = _____ arc sec**

11. To figure out how to scale the optical/lensing image to match up with the optical and x-ray Fits files we have in js9, we need to know how large these regions are. In js9, go under **File** and choose your DSS1 Fits file. Go to **Regions>circle**. A green circle will appear. Click this circle to get a blue resizing box. Drag one corner of the box until the diameter of the region is the same size as the js9 window. With the region still selected, go to **Regions>list**. The last number in parentheses is the radius of the circular region in arc sec. Double this to get the diameter. **Radius = _____ Diameter = _____**

12. To determine what the zoom should be of the optical/lensing jpg in js9, divide the scale of this image in arc sec (step #10) by the scale of your fits files (step #11). **Zoom = _____**

13. Go to **File** and choose the jpg. Go to **Zoom>numeric zoom** and enter your number from step #12.

14. Now for the artistic part! Go to **File** and choose the DSS1 FITS file (this is the optical data). Try **Scale>linear** and adjust the contrast and bias so that you can see the optical sources, but minimize the background. Contrast and bias are changed by holding the mouse down and moving left/right or up/down. If you want to start over, go to **Color>reset contrast & bias**. Choose a colormap from **Color**.

15. Repeat step #14 for the x-ray FITS which will start with "acis." Choose a different color map than you did with the optical FITS file. You can also play with **Scale**. We had changed it to "log" before to better see the data. You can also try "linear" or other scales.

16. To make the composite image of your optical, x-ray and optical/lensing, go to **View>Blending**. All three images should be automatically checked with a default of "screen" and "opaque. Check **Image Blending** at the top.

17. You may now notice that the optical FITS file and the optical/lensing jpg are not perfectly lined up. If you can't see this, go back to **File** and choose the DSS1 FITS file and change

the color map to something very different like **red**. Go to **File** and choose *1e0657_opt_lens.jpg* so that it is on top. Go to **View>panner**. In the panner window, move the green box so that the optical sources in the optical/lensing jpg align more closely with the ones in the optical FITS file. Under **Zoom**, you can also rotate the file by entering the number of degrees under **rotation angle**. When you have these two images lined up as closely as you can (and it probably won't be perfect), you can go back to each of your FITS files individually and play with color maps and contrast and bias until you have the image you want.**

18. One last tweak, go to **File>Image Filters** and try adjusting the "blur."

****NOTE:** If you would like more control over the colors and contrast and bias for the optical/lensing map, you can convert this to a FITS file. With *1e0657_opt_lens.jpg* chosen, go to **File>save>FITS.** Then go to **File>close>this image** and then **File>open local** and find *1e0657_opt_lens.fits* on your computer. Follow the procedures you did before as far as scaling and lining it up. Now you may choose your own color map and adjust the contrast and bias for this image.

Analysis and Conclusions:

1. Use a region in js9 to determine the approximate diameter of the Bullet Cluster in arc seconds. Explain your method.

2. Using the small angle formula, the diameter in arc sec (from #1), and the distance found in the Fast Facts section of the Chandra Photo Album page for the Bullet cluster, determine the approximate size of the Bullet Cluster in light years. Show your work below.

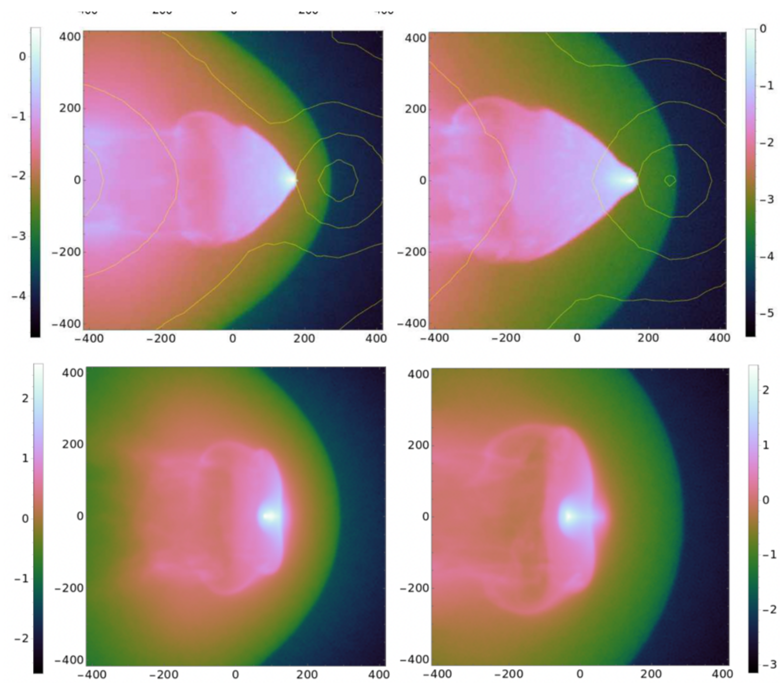
$$\theta_{\text{arc sec}} = 206265(\text{size}/\text{distance})$$

3. How does the size of the Bullet Cluster compare to that of the Milky Way which is ~100,000 ly? Which makes more sense, that the Bullet Cluster is the collision of a cluster of stars or a cluster of galaxies? Explain.

4. What is most likely producing the x-rays in the image you formed? How might you explain the separation between the right and left sides? Use your image and the background information to justify your answers.

5. The blue areas in the optical/lensing image show where astronomers find most of the mass in the clusters as mapped by gravitational lensing. Does it seem to be moving faster or slower than what is producing the x-ray emission? Explain.

"In some cases, X-rays show a gas bullet with a protruding head and pronounced shoulders. We point out that these features, while difficult to explain without dark matter (DM), naturally arise as the head of the slowed-down gas is gravitationally pulled forward toward its unhindered DM counterpart." In the image below, the top row is produced by a simulation of a gas/dark matter interaction and the bottom row by a gas/gas interaction. (Keshet, Raveh, Naor 2021)



6. Which row in the image above, most closely resembles the shape of the Bullet Cluster?

7. Does the Bullet Cluster seem to give evidence for the existence of dark matter? Explain, giving results from your analysis and using the background information.

EXTENSIONS AND ALTERNATIVE EXPLANATIONS:

Conduct an investigation on what data of colliding galaxy clusters says about the presence of large amounts of antimatter in the universe. Include a discussion of what antimatter is and in what band of the electromagnetic spectrum observations should be made to show its presence.

If possible, find a FITS file from an observation of the Bullet Cluster in this band of the electromagnetic spectrum to upload into js9. You may wish to look at the Heasarc Search page:

https://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3browse.pl

Bibliography:

Chandra Press Room :: NASA's Hubble, Chandra Find Clues That May Help Identify Dark Matter :: 26 March 15, https://chandra.harvard.edu/press/15_releases/press_032615.html.

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Keshet, Uri, et al. "Protruding Bullet Heads Indicating Dark Matter Pull." *Monthly Notices of the Royal Astronomical Society*, vol. 508, no. 3, 2021, pp. 3455–3462., https://arxiv.org/abs/2101.06271

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Steigman, Gary. "When Clusters Collide: Constraints on Antimatter on the Largest Scales." *Journal of Cosmology and Astroparticle Physics*, vol. 2008, no. 10, 2008, p. 001., https://arxiv.org/abs/0808.1122.

3. RA = 6:58:37.9 Dec = -55:57:0
10. height= 5.4 arc min = 324 arc sec
11. Radius = 216.277078" Diameter = 432.554156”
12. Zoom = 0.75
17. Zoom of 0.74 and rotation of 358 works well