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# *Chandra* X-Ray Observatory - First Year Science Highlights

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**Abstract.** The *Chandra* X-ray Observatory achieved orbit on July 23, 1999, and began science observing in October 1999. Now over a year since the first light image of Cas-A, *Chandra* has observed several hundred science targets and many calibration objects. A few highlights from these data are presented - including a discussion of the spatially resolved spectrum of supernova ejecta in Cas-A and X-ray emission from the central regions of M31, the nearby AGN Cen-A, and the quasar 3C273.

## 1. Introduction

The launch, on July 23, 1999 of the *Chandra* X-ray Observatory heralded the second golden age of X-ray astronomy. *Chandra* brings to the field sub-arcsecond imaging that is comparable to ground based optical astronomy. With the Advanced CCD Imaging Spectrometer (ACIS; Garmire 97) and the High Resolution Camera (HRC; Murray 98) in the focal plane, and two Transmission Grating Spectrometers (LETGS, Brinkman 2000; HETGS, Markert 1994), *Chandra* gives astronomers a new view of the X-ray Universe that is sharper and deeper than ever before. This science highlight presentation will illustrate the power and potential of *Chandra* by showing some of the early results that have been obtained.

## 2. Cas-A

This supernova remnant (SNR) has long been studied. It was selected as the official first light image for *Chandra* because of its complex spatial extent and its high X-ray brightness. As seen in Figure 1 the X-ray emission is complex - it is easy to note the nearly circular shape of the SNR and the shell-like appearance that was already known from previous observations. However, in viewing the central part of the SNR *Chandra* for the first time revealed a point-like source that lies very near the center of expansion of the source (Tananbaum 1999). This compact central object was one of the first surprises from *Chandra*, and if truly associated with Cas-A, it is likely to be the end product of the core collapse of the progenitor star that lead to the supernova explosion of some 320 years ago.

The X-ray data (taken with the ACIS) also provide the X-ray energy distribution at each part of the image (spatially resolved spectroscopy); this is illustrated in Figure 1 by the various colors assigned to the image pixels. The lowest energy photons are colored red, intermediate energies are green, and the highest energies are blue. This representation shows how the spectrum of X-ray

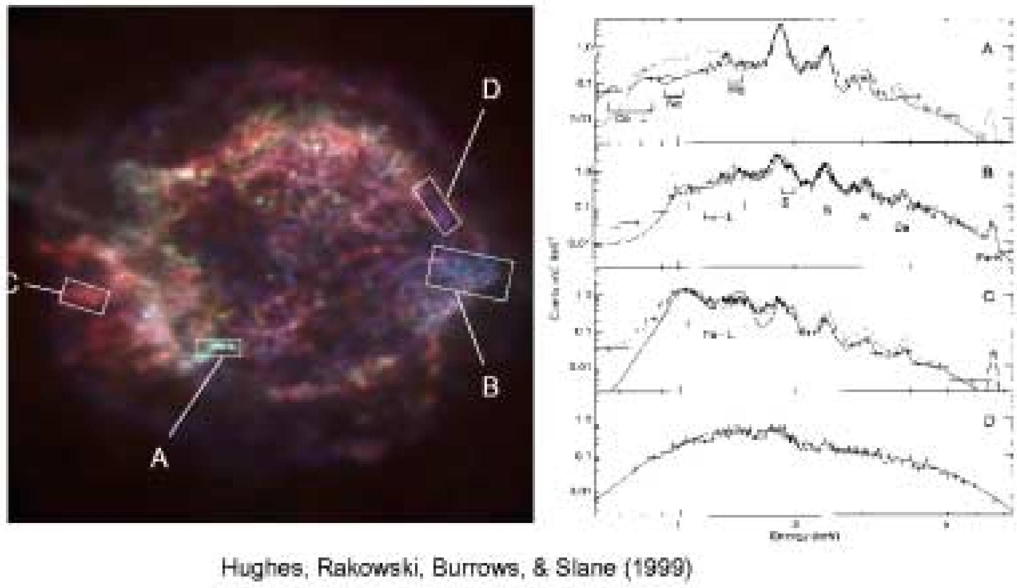


Figure 1. Cas-A spatially resolved spectra, from Hughes et al. (2000).

emission changes over the remnant. This effect can be seen in more detail in the work done by Hughes et al. (2000). As shown in Figure 1 several regions were selected from the image, and the X-ray spectrum was plotted versus an expected spectrum for a particular model of SNR ejecta. As discussed by Hughes et al. the selected spectra vary considerably, and represent material thrown out from different layers of the core of the collapsing star during the supernova explosion. Interestingly, the material from the inner-most layers of the core has traveled out to the edge of the remnant as indicated by the presence of iron in the X-ray spectrum. This effect is probably due to differences in the ejection velocity of the core layers as the collapse evolves. It provides important observational data for the theorists to match in their detailed numerical calculations for these events.

Figure 2 shows a 50 ksec observation of Cas-A that was taken with the HRC. In this image, the central compact object is clearly seen. There are about 4,000,000 events from Cas-A in this image, and only about 1500 of them are from the central source. The excellent quality of the *Chandra* mirrors, particularly their high angular resolution and low scattering, is essential for separating the point source from the surrounding nebula. The purpose of this long HRC observation is to search for a periodic signal from the compact object. This signal, if found, would confirm the association of the point source with a neutron star that should have been formed during the supernova explosion. At the time of this writing, the data are still undergoing analysis, and results are not yet available.

These observations demonstrate the importance of coupling image processing and display systems with data analysis software. Defining regions of interest in an image to select data of interest from a non-spatially sorted data set (as for example the photon event list from *Chandra*) is an important tool needed for science analysis. Similarly the tools needed for detailed timing analysis present

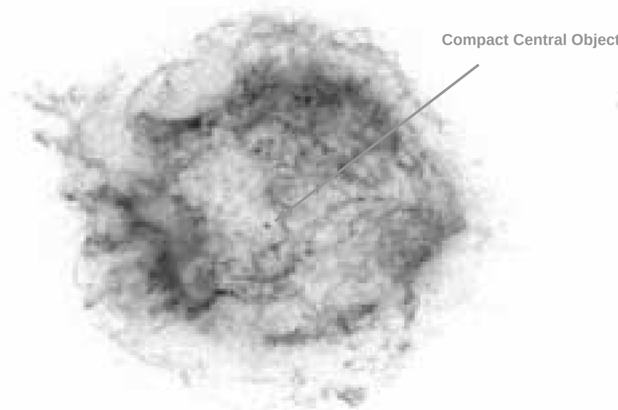


Figure 2. HRC image of Cas-A

a challenge to the *Chandra* data system. Not only must the proper events be easily selected (as for the spectral analysis case), but there are systematic time corrections, such as accounting for orbital motion, that need to be accurately applied to the data before any temporal analysis can be performed. Searching for periods is known to be a compute intensive task. Developing efficient algorithms to implement the search (e.g., FFT, period folds, and other statistical tools) is an important need of the scientist.

## 3. M31

The *Chandra* monitoring program for M31 (our nearest neighbor galaxy, Andromeda) has provided several interesting results. Figure 3 shows a comparison of ROSAT and *Chandra* images of the central region of M31. These images are on the same spatial scale, and illustrate that the sharpness of the *Chandra* telescope achieved in just 15 ksec what took much longer with ROSAT.

Figure 4 shows the central region of the galaxy. Here the circle represents a $5''$ radius about the galaxy center. Where ROSAT detected a single source, *Chandra* resolves five individual point sources. One of these is likely to be associated with the actual center of M31, where there is a $3 \times 10^7 M_\odot$ black hole (BH). The two *Chandra* sources closest to the BH location are just $0.5''$ apart.

It will take some additional work to determine which of these sources is most likely the central source. One has an unusually soft X-ray spectrum, a characteristic associated with a class of objects known as super-soft sources (SSS's). The other appears to be typical of most galactic X-ray sources. The SSS is quite variable in intensity (about a factor of 5-10 within a few months). However,

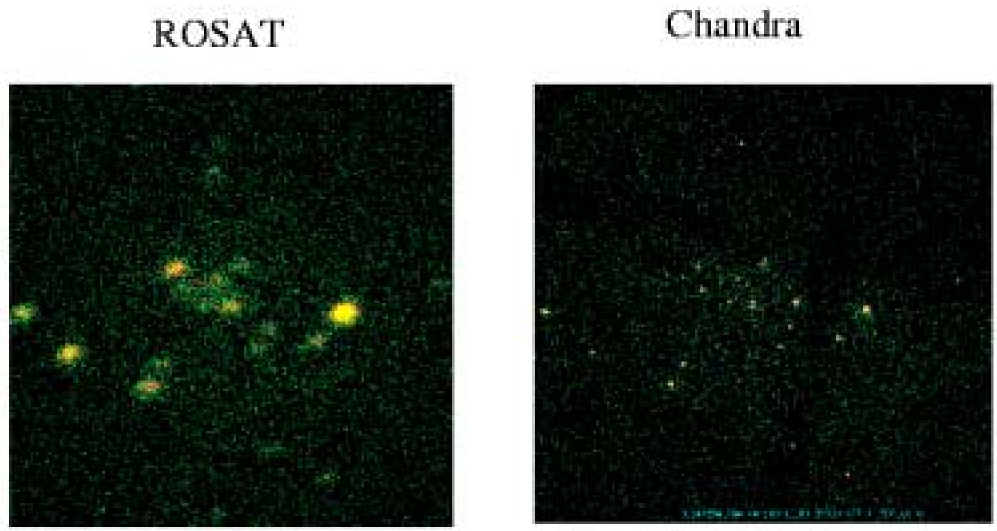


Figure 3. Comparison of ROSAT and *Chandra* images of the central region of M31 (Andromeda), our nearest neighbor spiral galaxy

none of these properties is sufficient to confidently determine an association of the black hole with the center of M31. Monitoring of the region is continuing to improve the absolute locations. HST images of the center of M31 provide matches between *Chandra* and HST sources so that the coordinates can be accurately aligned. If successful, this work will eventually lead to $0.2''$ precision in locating the center of M31 with respect to the X-ray sources.

The role of astronomical software in helping to process, analyze, and understand the data from M31 is critical to progress. In the case of M31, the entire galaxy is too large to be observed in a single detector field of view. Mosaic images are needed to give a complete view. This process requires algorithms for translating images onto a larger frame, retaining all of the information and taking into account edge effects from the detectors and telescope. Exposure maps and corrections are needed, particularly in areas of overlap, so that proper source intensities and light curves can be constructed. Stacking repeated images, as in the central region of M31, is another challenge for software developers. Easy methods for co-aligning images and calculating combined exposures are required for such observations. Matching data from *Chandra* and HST involves careful calculations of source centroids, transformations of coordinates, and accounting for detailed differences in the astrometry from each mission.

## 4. Cen-A

The *Chandra* Observatory makes it possible to study in great detail the X-ray properties of the nearest active galactic nucleus (AGN) source Cen-A (or NGC 5128). This galaxy is about 3 Mpc distant, implying that $1'$ corresponds to about 1 kpc in linear dimension. Thus with $1''$ image quality, it is possible to observe

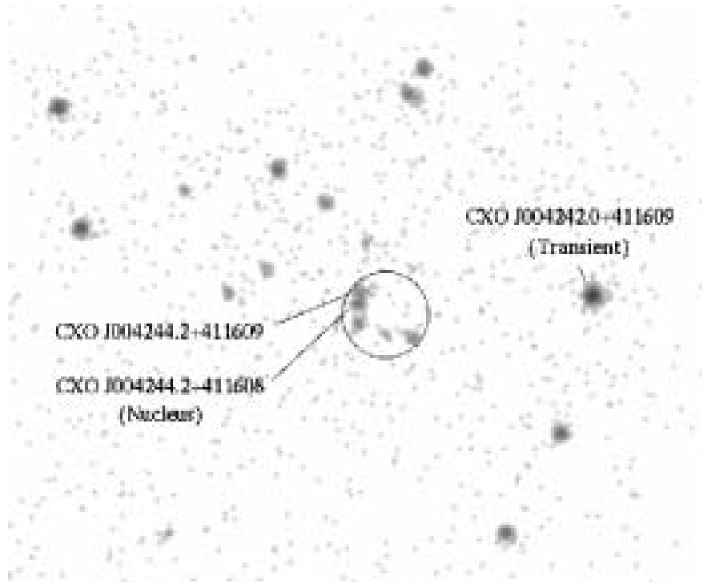


Figure 4. The nucleus of M31 as seen in X-rays by *Chandra*

X-ray phenomena on the linear scale of about 15 pc (45 ly). This is the scale of distances between our sun and neighboring stars.

Figure 5 shows X-ray images obtained with the HRC and ACIS. In both images it is easy to see the strong central nucleus that is being powered by a super massive black hole (about $3 \times 10^7 M_\odot$) and a long one sided jet of emission directed to the northeast. The jet consists of many bright knots embedded in what appears to be a well collimated diffuse emission region. The jet extends at least $6'$ from the nucleus.

In Figure 6, the X-ray emission is compared with radio data taken at 13 and 6 cm wavelengths. The 13 cm radio data emphasizes the large scale structure from Cen-A and shows what are called the inner radio lobes that extend to the northeast and southwest, as well as the jet. There is excellent correspondence between the X-ray and radio data when viewed on a large scale. Of special interest is the bright X-ray ridge of emission that corresponds to the edge of the southwest radio lobe. This ridge was barely detected in previous X-ray observations (e.g., *Einstein* and ROSAT) but is now seen clearly. It is very closely aligned with the edge of the radio emission. The southwest radio lobe is actually filled with diffuse X-ray emission, with the region of peak radio emission inside the lobe corresponding to the minimum X-ray emission region. Understanding the details of the physical conditions at Cen-A that give rise to these correspondences is the goal of this investigation. The ACIS can extract spatially resolved X-ray spectra at different locations in the image for studying the spectral changes as a function of location as an indicator of changes in the properties of the emitting material.

The second panel in Figure 6 shows the radio emission at 6 cm plotted over the X-ray image along the jet. Again there is good general correspondence between the radio and X-ray image. However, at the detailed level, there are some

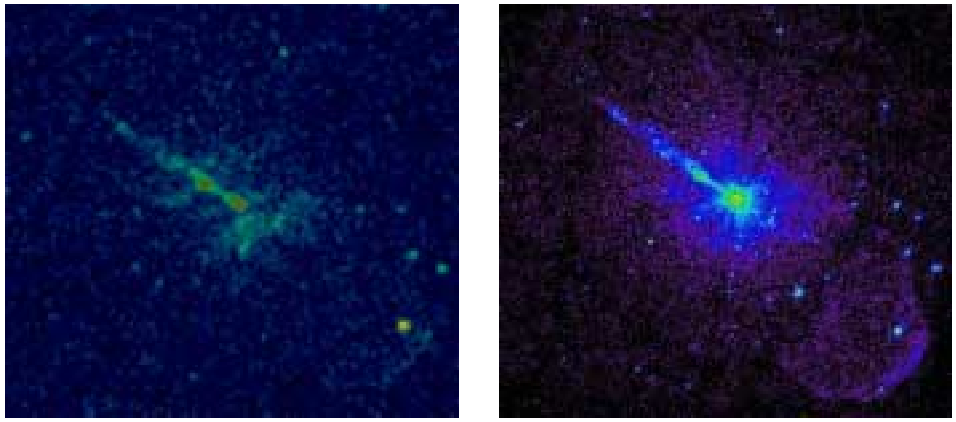

Figure 5. *Chandra* images of Cen-A HRC and ACIS

striking differences. While peaks in the X-ray and radio emission correspond for the innermost knot in the jet, farther out from the nucleus the correspondence becomes less precise, and the peaks in X-ray emission lie closer to the nucleus than the corresponding radio peaks. This change in the relative locations of peak X-ray and radio emission indicates that there is likely to be a lot of shock formation, particle re-acceleration, and radiation going on along the path of the jet. The knots may well be sites of shocks from which accelerated particles propagate outward, losing energy to radiation. The higher energy particles lose their energy faster so that the spectrum softens farther from a shock. The detailed processes along the jet are much more complex at the scale of *Chandra* resolution than was evident from lower resolution observations.

The astronomical software impact for studying these data follows many of the points already discussed. A new process used for looking at complex images is seen in the adaptively smoothed image of Figure 6. This is an example of image processing that helps to highlight features on differing spatial scales making visual inspection easier. Various algorithms for this class of image processing are possible, and typically there are many parameters that can be set for these algorithms. Having well constructed software that can run efficiently and reliably to implement these processes is critical to their use. Being able to quickly run many cases of an adaptive smooth, for example, varying parameters to bring out desired features or suppress noise, allows a researcher to develop a sense of what is important and what is real in an image. Similarly, detecting sources in complex images such as Cen-A is an intriguing problem. Using wavelet decomposition, percolation techniques, or standard sliding box detect algorithms, each gives a particular advantage and disadvantage in the task of extracting information from an image. In practice all of these methods (as well as others not discussed here) should be tried and compared in order to obtain the most reliable results. The ease of use of these techniques, as well as their running time, often dictates what is actually done. Astronomical software developers need to work with scientists to make this task as easy and complete as possible.

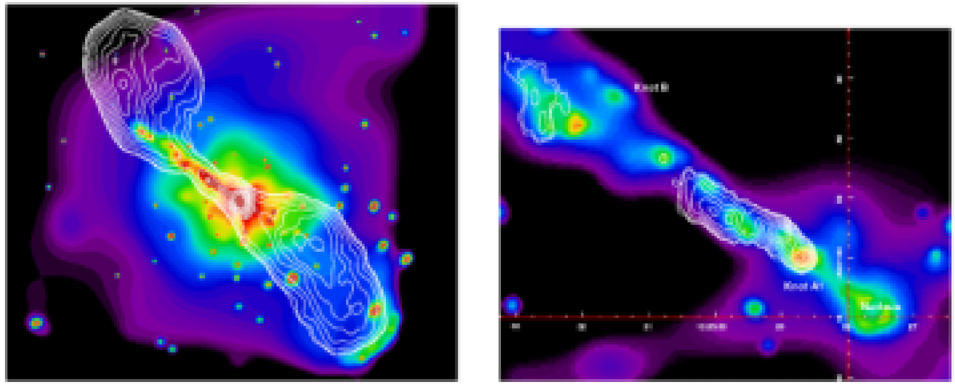

Figure 6. Radio and X-ray comparison for Cen-A

## 5. 3C273

A final example of recent *Chandra* results, shown in Figure 7, is the image obtained using the HRC to observe the quasar 3C273, a well known bright QSO. Associated with the source is a jet that extends over hundreds of kpc. Thanks to the resolution and low mirror scatter of *Chandra*, this jet is easily detected even though there are just 1300 photons in that part of the image, as compared with over 225,000 photons from the central point source. *Chandra* image quality allows X-ray emission from the jet to be resolved into at least three components. The first bright knot along the jet may itself be slightly extended. The other two knots are too faint to detect any such extent.

Figure 8 shows a composite of images of the jet of 3C273 taken in the radio, optical and X-ray bands. It is apparent that the jet behaves differently at these three wavelengths: the X-ray image becomes fainter farther from the nucleus, the radio image gets brighter, and the optical remains largely constant - although fragmented into many knots. As for Cen-A, this comparison suggests that the physical processes responsible for emission are varying along the jet. The closest knot is well fit to a synchrotron model, while this model fits less well for the jet region farther along and fits rather poorly at the jet's end. Physical conditions along the jet are changing – not surprising since the jet is the size of our Milky Way Galaxy. More complex models must be considered if radio, optical, and X-ray emission is to be jointly understood and interpreted.

The observation of 3C273 illustrates the need to be able to simultaneously consider the multi-dimensional problem of spatially resolved spectroscopy across broad wavelength bands. The development of data-cubes, for representing the information, and then processes that can act on these large data items, appears to be the direction for the future. *Chandra* is only the first of several next generation observatories that will require such data types and processes.

## 6. Conclusion

The launch and operation of *Chandra* has brought a flood of exciting new data into the hands of observers. The tremendous detail and richness of *Chandra*

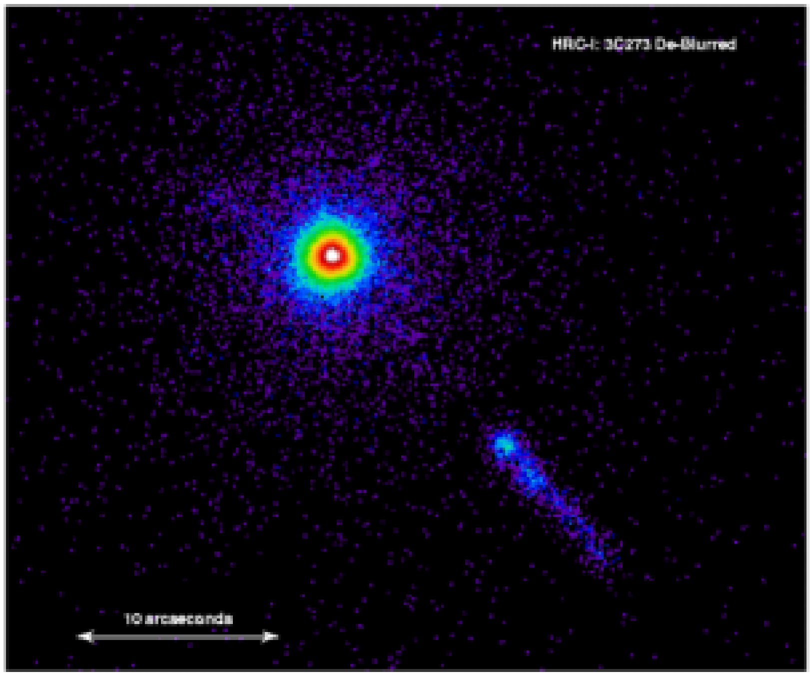


Figure 7. HRC Image of 3C273

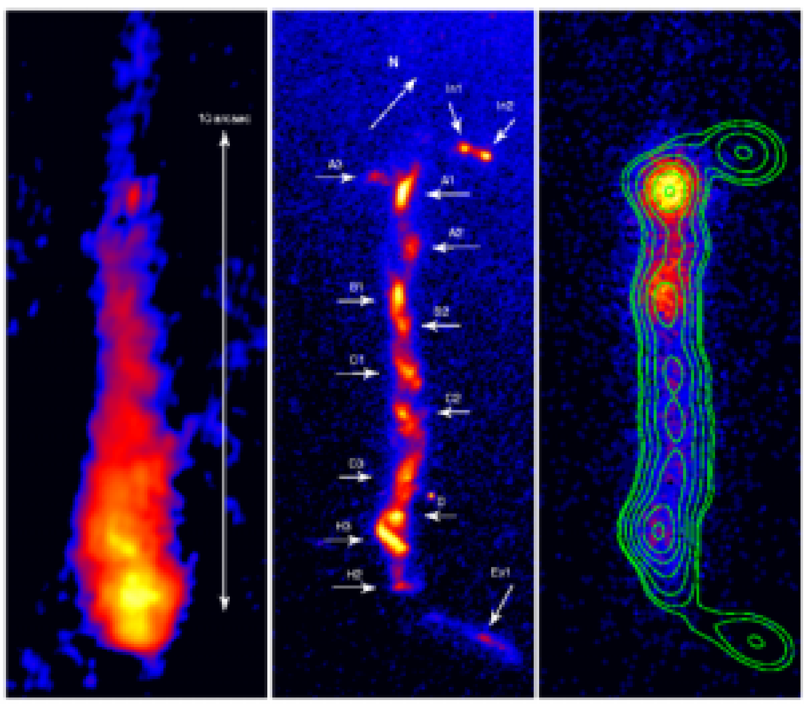

Figure 8. Jet of 3C273 shown in radio, optical and X-ray bands

data, especially when combined with observations in other bands (radio, IR, optical, UV, etc) places new demands on astronomical software. The volume of data is growing along with its complexity. This growth leads to needs for faster, more capable computer systems to deal with the data, but more importantly, it places greater demands on the types of analysis and presentation software. The modern astronomer needs interactive image display, data selection tools, filters and algorithms that work in an integrated fashion to allow for coherent, rapid data analysis. The science productivity of a mission such as *Chandra* depends as heavily on the capabilities of astronomical software as it does on the technological innovations of the observatory. From these few examples of what *Chandra* data look like and how their analysis and interpretation depend on the data systems available, it is clear that much progress toward the required software capabilities for processing *Chandra* data has already been made (if this weren't true, the above images could not have been presented!). Further progress is almost certainly needed in the area of science analysis tools that realize the full potential for interpretation and understanding of the information in images such as the ones presented here. It is these latter needs that the ADASS community must address. One can hope that the new data systems software to emerge in the near future will produce many satisfied customers.

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