H-α Imaging of an Old Neutral Shell in the ISM

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ABSTRACT

Located between the stars is a very low-density material consisting of gas and dust, called the interstellar medium (ISM). New stars form from this material and when massive stars die, they explode sending enriched material outward to interact with the ISM, often producing a shell-like structure. Interactions between such shells and the ISM are essential steps in the cosmic recycling that produces the next generation of stars.

Most well-studied shells are younger shells that are expanding into the surrounding ISM. This project studied an old shell, located at galactic coordinates $(l,b) \sim (192°, +6°)$, that has stopped expanding. It was discovered in the neutral hydrogen SETHI dataset. High-resolution H-α images of the ionized gas were taken at the Kitt Peak National Observatory using the WIYN 0.9m telescope with the MOSAIC camera. The individual H-α images will be combined into a large mosaic image of the shell and compared to existing images of the shell in other wavelengths. By looking at data across the whole spectrum of light, the various interactions of the shell with the ISM can be explored. Data reduction, analysis, and results will be discussed below.

INTRODUCTION

Despite appearing filled with stars, galaxies, and numerous other objects, the universe is mostly just space. However, this space is not as empty as it might seem. It is actually filled with a low-density gas called the interstellar medium (ISM). It's the great recycling factory in the universe. Stars form out of this material, and when they die, they replenish the ISM with heavier elements in the gases. When stars explode in brilliant supernovae, the ISM is disturbed, causing irregularities. One example of such an object is a shell of material that expands outward from the central star. These newly formed disturbances are crucial to the formation of the next generation of stars, so a good knowledge of the properties of the ISM is essential to understanding stellar and galactic evolution.

The ISM in the disk of our galaxy has both cold, dense and hot, ionized components. The physical state and evolution of these gas phases have been broadly explained by the theories of McKee-Ostriker (1977) and Cox and Smith (1974), but there are still many outstanding problems with both these and all other current models of the ISM. Detailed study of the interactions of particular supernova remnants (SNRs) with their environment will improve our understanding of the overall processes in the ISM. According to models of interstellar material in our galaxy, old SNRs should be everywhere.

Comparison of observations of supernova remnants at multiple wavelengths is an essential part of the process. An example of such a comparison is the Cygnus Loop SNR. From 1992 to 2003, it was studied at radio, optical, far-ultraviolet, and X-ray wavelengths, yielding both spectroscopic and imaging information. All of these observations have contributed to our understanding of the object. Says one researcher about such shells, "the multi-wavelength whole is far more than the sum of its parts." (Heiles, Haffner & Reynolds 1999)

The shell studied in this project was identified by Dr. Eric Korpela in the SETHI (Search for Extraterrestrial HI) database (Korpela et al 2004), which is a collection of velocity-resolved cold, neutral hydrogen maps taken with the Arecibo radio telescope at the 21cm wavelength. Figure 1 shows the shell's 21cm emission. It is located at $(l,b) \sim (192°, +6°)$ with a brightness of ~15Ry over the darker center of the SNR. One Rayleigh (1 Ry) is defined as $10^{10}/4\pi$ photons per square meter per second per steradian. A steradian is a measurement of solid angle, a squared radian. The SETHI radio survey of neutral hydrogen (HI) has better sensitivity and resolution than any previous survey. (e.g. Korpela et al 2002) This allows identification of previously overlooked shells, like the shell this project is focused on. Thorough follow-up observations of these shells are essential to further our knowledge of the ISM.
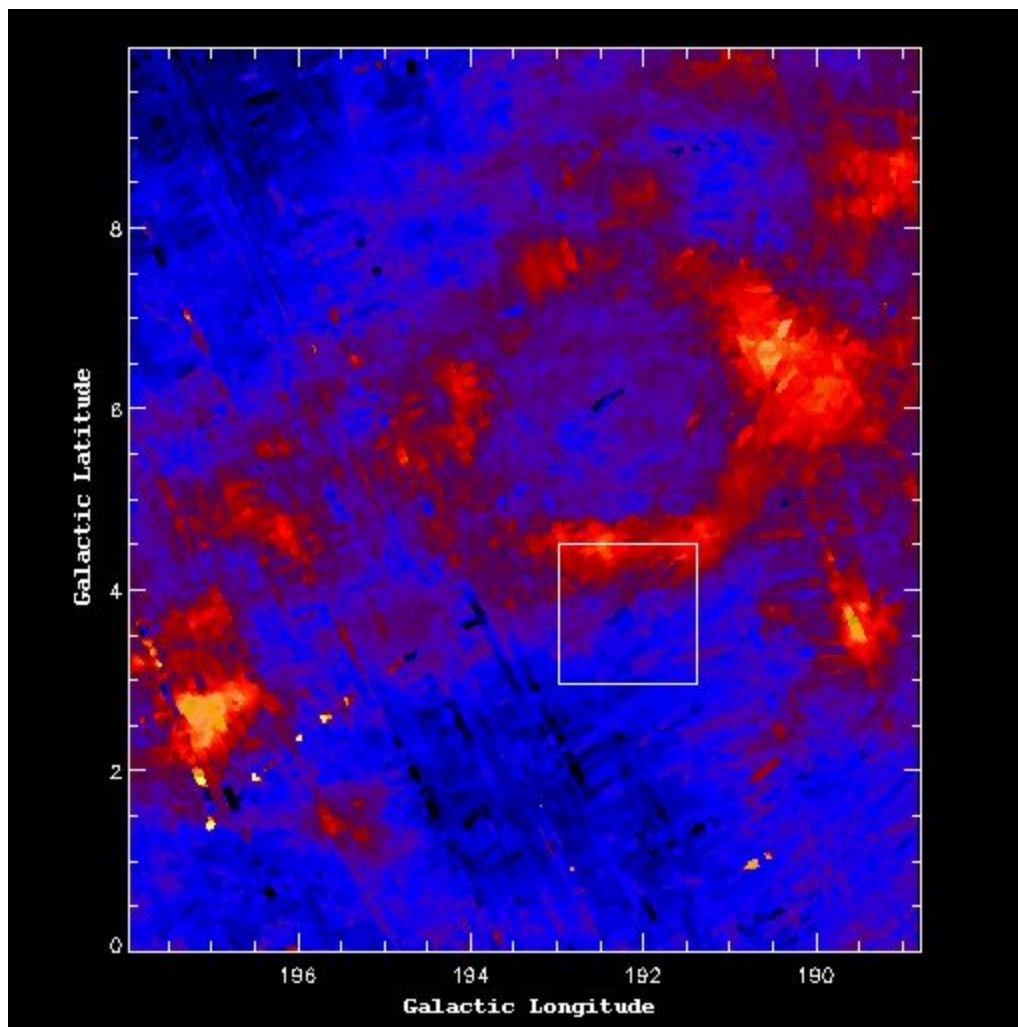
Figure 1. The shell in HI (neutral hydrogen) from the SETHI database. Red represents regions of strong 21-cm emission.

This shell is interesting because, unlike most well-studied shells, it has ceased expanding into the surrounding medium. Young shells emit X-rays due to the intense heat left over from the supernovae that created them. As shells age, they cool very slowly because they have a low density. As this shell has a low X-ray surface brightness, it is believed to be old. Also, the radial velocity of the gas can be measured by observing the Doppler shift of the 21cm emission. This shell is observed almost entirely at one velocity, moving 15km/s towards us, showing that it is moving together, rather than expanding.

This project maps the shell at high angular resolution in H-α emission (656.281 nm) to study its warm, ionized hydrogen components. The map created though this research will be an improvement over the map shown in Figure 2. Ionized electrons in the gas recombine with the hydrogen nucleus, cascading down though energy levels, causing the emission of the H-α line. These will be compared to the shell's cooler neutral hydrogen components, from the SETHI database, to learn more about the physical processes at work. They will be compared to archival data at other wavelengths as well. X-rays map the hot gas in the shell, while radio wavelengths reveal the cold gas.
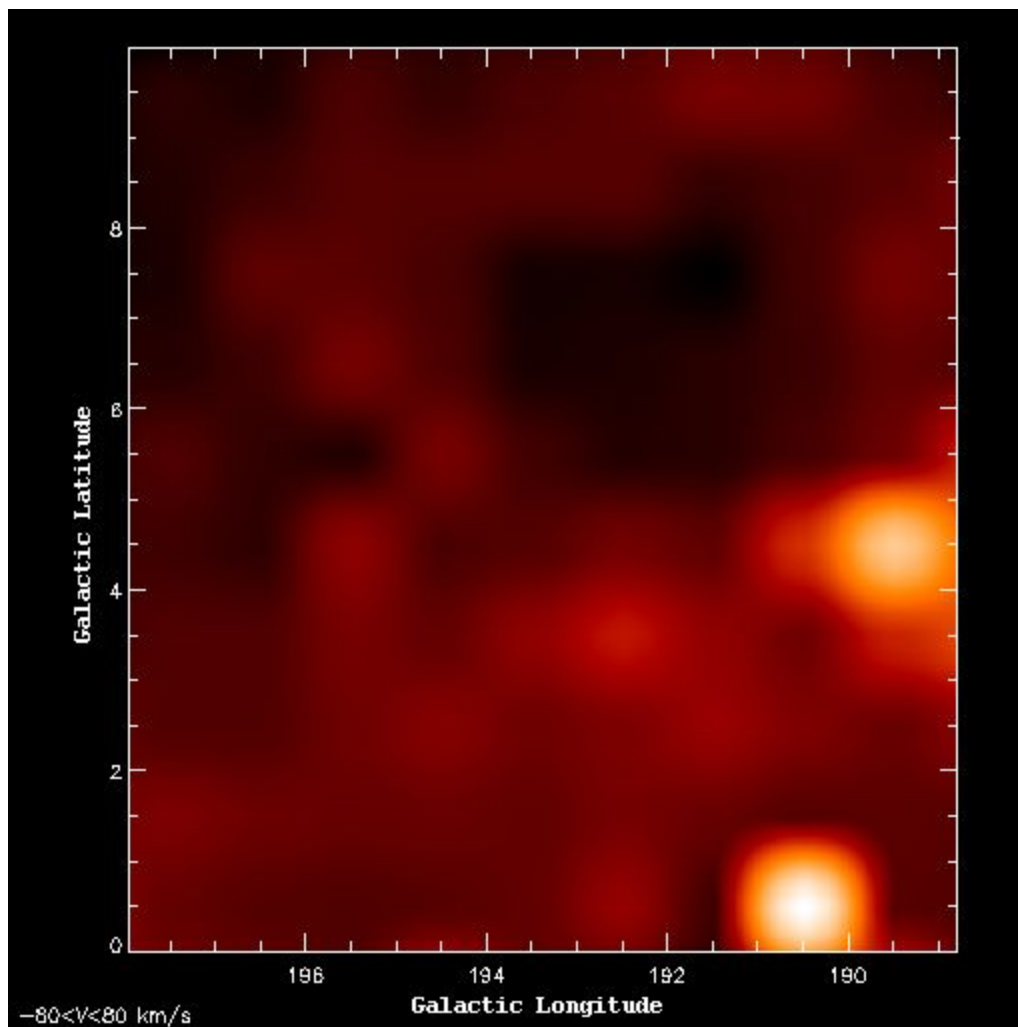
Figure 2. Existing WHAM (Wisconsin H-α Mapper) image of the shell in H-α. (Haffner et al 2003)

OBSERVATIONS

The images for this project were taken at the Kitt Peak National Observatory in Kitt Peak, Arizona, with the 0.9m WIYN telescope. Data were gathered on two separate observing runs. The data were taken February 7-9, 2004 and January 16-18, 2006. The MOSAIC camera was used to take the images. It is composed of 8 CCD chips that combine to form an 8k x 8k pixel array that can image nearly 1 square degree of the sky.

The images of the shell were taken with 20-minute exposure times. The filter used was the H-α k1009 which has a central wavelength of 657.474 nm and a FWHM (Full-Width Half-Max) of 8.062 nm. Shorter 60-second exposures were taken of the same fields with an R filter to allow continuum removal. The images were taken in sets of 3 with offsets of 450 arcseconds in right-ascension and 250 arcseconds in declination between each image to fill in the gaps between the CCD chips. Calibration images, including flats and biases, were also acquired.

DATA REDUCTION AND ANALYSIS

The data were reduced using IRAF[1] (Image Reducation and Analysis Facility; Tody 1986 and 1993), a data reduction package that runs in Linux. IRAF performs corrections for bad pixels, crosstalk between CCDs, overscan and bias, and flat-field. It also aligns and stacks images. A sample image of raw data is shown in Figure 3.

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[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

IRAF automatically corrects for the crosstalk. Once that is done, the next correction that was applied is called the zero-level or bias correction. When the data is read out from the telescope to the computer, a read-out noise exists. This read-out noise changes both spatially across the CCD chip and over time because the electronic noise in the CCD varies with temperature and time. An example of this noise can be seen as a bright vertical band to the right of #1 in Figure 3. It is also responsible for the abrupt changes in brightness level between chips. To correct for the temporal variations, each image has an "overscan region". This region records the zero-level throughout the night, allowing us to track how the zero-level changes with time. We used this overscan region to first correct our images for the time variations. The IRAF command *zerocombine* was then used to combine the individual overscan-corrected zero-level (bias) images for processing. During the combination of images, outlier pixels were removed. This combined zero image was then used to correct the other overscan-corrected images for spatial variations.

The third correction performed is called the flat-field correction. Each chip in the CCD has a varying sensitivity to light, causing brightness differences across any image, as well as other anomalies. An example of these differences can be seen in the region around #2 in Figure 3. Another anomaly corrected by flat-fielding is called the dust donut. Dust particles on the optics appear as out-of-focus donut-shaped shadows, as shown at #3. To correct for these, the CCD is exposed to a uniform illumination, giving a "flat-field image" which reflects the CCD response. There are two types of flat-field images. The first kind is taken with the telescope looking at a patch of flat, twilight sky, called a twilight-flat. The second kind is taken with the telescope looking at a flat white surface illuminated with dome lamps. This gives us a dome-flat image. Several flat-field exposures were combined using the IRAF command *flatcombine* or *sflatcombine*, the overscan and bias levels removed, then the images were normalized to a median value, and used to correct our images. Again, during the combination, outlier pixels were removed. Figure 4 shows the same field as Figure 3 but with the corrections applied.
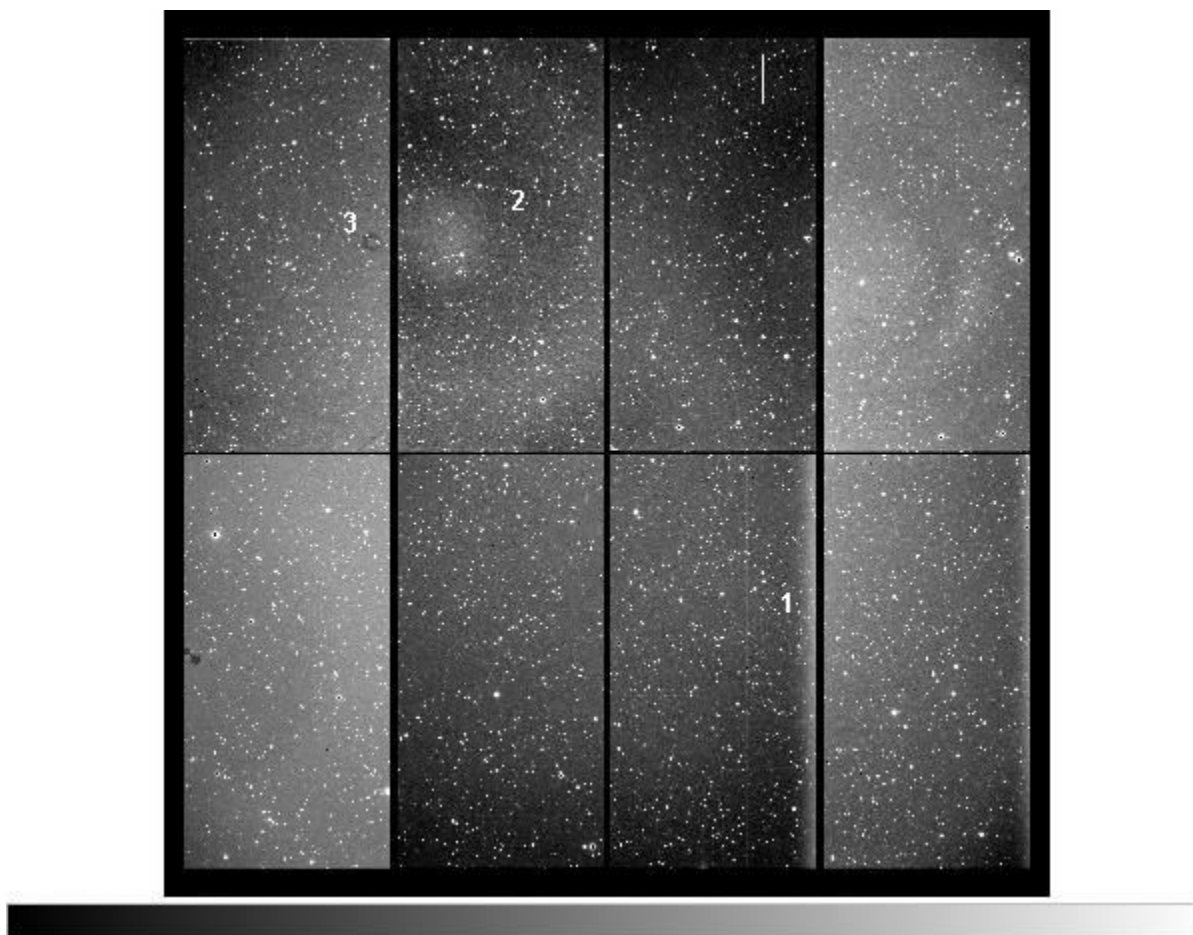
Figure 3. A raw image from MOSAIC. See text for a description of the features corresponding to the numbers.
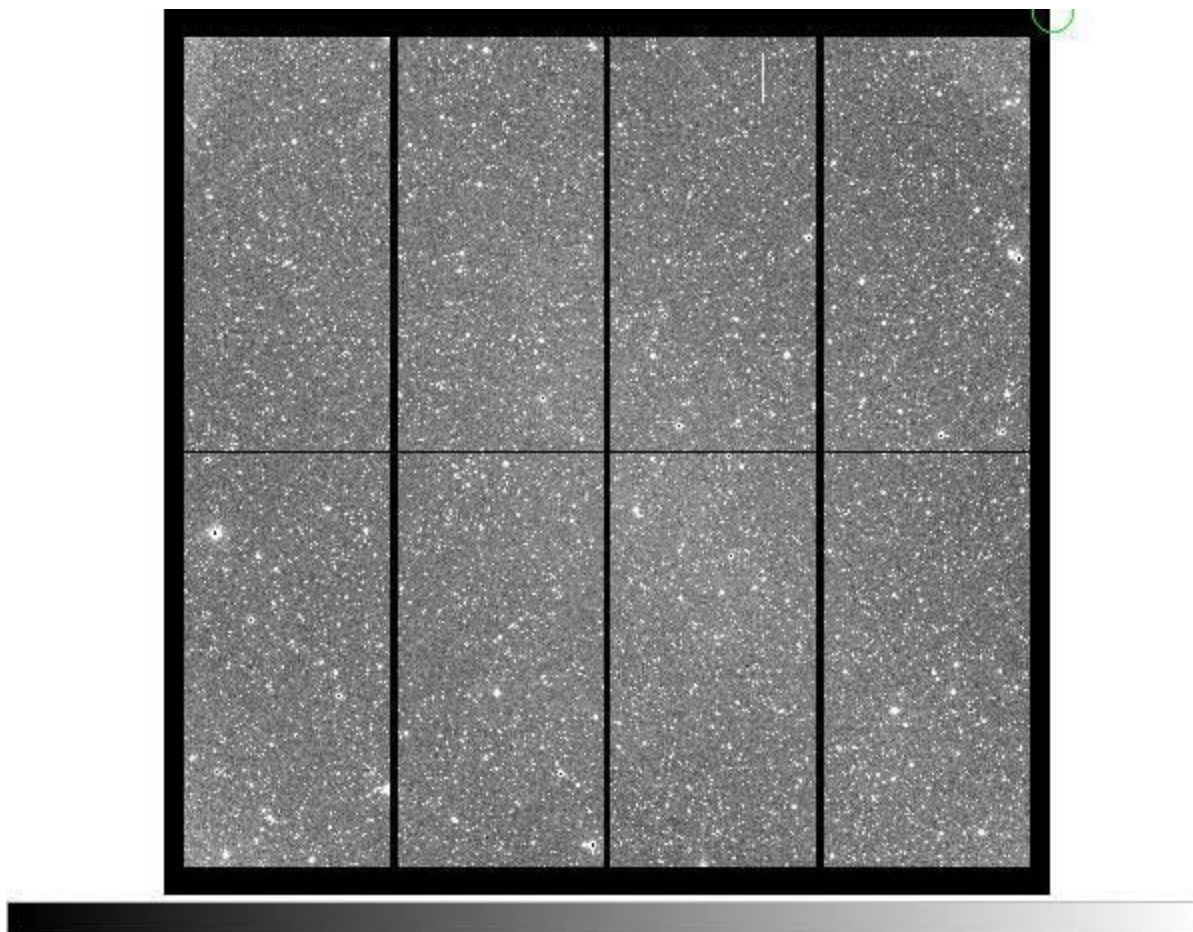
Figure 4. An image showing the same field as Figure 3 but with instrumental corrections applied.

After the images are corrected for the instrumental effects, the offset images were aligned to a world coordinate system so that they could be stacked together. This was slightly complicated because the pixel to coordinate mapping is non-linear. Stars in the images are used to align the images to the world coordinate system. A catalog of stars (USNO A2) was downloaded from http://www.nofs.navy.mil/data/FchPix/ and used as the coordinates to match with the stars. The IRAF task *msczero* is used to perform the 0th order position offset from the stars to the coordinates, using a catalog down to 12th magnitude, and *msccmatch* is used to account for the non-linear spatial variation, using a catalog down to 15th magnitude.

Finally, the stars are removed so that the subtle details of the ISM can be seen and the images will be stacked together to form a large mosaic of the shell. The IRAF task *daophot* is used to identify stars and fit a point-spread function to stars in the image. This point-spread function is then used to remove these stars from the images.

Figure 5 shows a sample region after the coordinate-matching and star-removal has been completed for a set of 3 images. The gaps in the images have also been filled in where the three images overlap. Comparing the neutral hydrogen distribution in the boxed area in Figure 1 with the same region showing ionized hydrogen in Figure 5, it is apparent that the two gases are not at the same locations within the shell. Careful measurements of emission at the 21-cm wavelength and H-α will help us determine the physical conditions in the interface between the shell and ISM.

Currently, the stars are being matched to a world-coordinate system and the stars are being removed, leaving the fainter detail of the ISM to be examined. Then the images will be stacked to form a large mosaic of the shell. Finally, the data can be analyzed and compared to maps in other wavelengths.
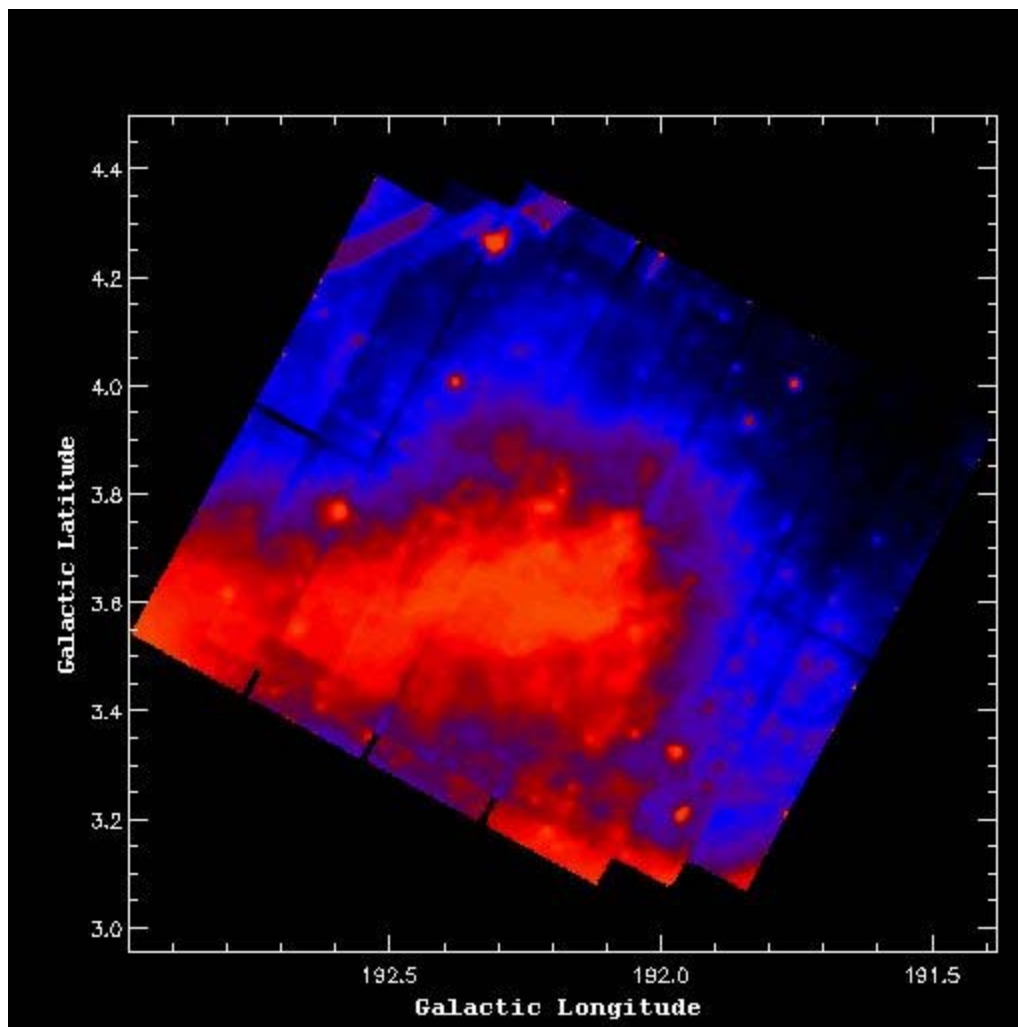
Figure 5. A sample triplet of stacked images showing H-α (ionized gas). Red represents regions of more H-α emission.

CONCLUSION

By comparing images of this shell in different wavelengths, it's possible to learn what processes are happening. For instance, shock ionization is caused by physical motions of gas while photo-ionization is caused by emissions from the central star. Different models predict various importances for each type of ionization.

Cooling processes will also be studied. For example, gas can cool by a process called collisional deexcitation. When gas particles collide, electrons in the gas particles become excited to higher energy levels. When the electrons return to lower orbits, they'll emit radiation that can escape the gas cloud, leaving the particles with a lower kinetic energy or temperature.

The high angular resolution maps produced by this project will allow us to study the turbulent interaction on very fine scales and give a detailed picture of the evolution of an old, evolved supernova remnant.

ACKNOWLEDGEMENTS

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