The Cygnus Loop/Veil Nebula
Hubble Space Telescope

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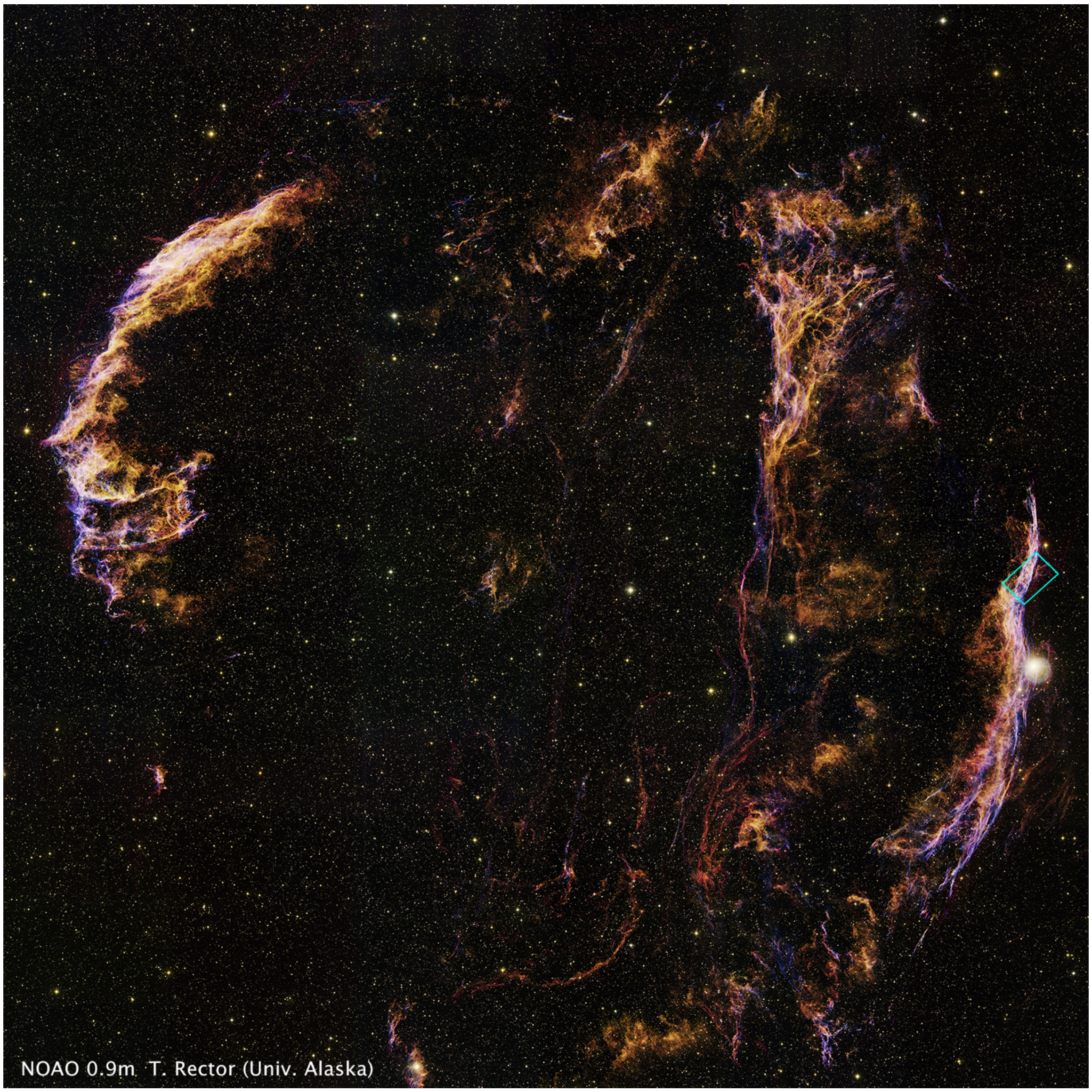
September, 2015

Overall context:

The Cygnus Loop, or Veil Nebula as it is sometimes called, is the expanding remains of a massive star (about 20 times the mass of the sun) that exploded some 5,000 – 10,000 years ago in our Milky Way galaxy. Its distance is still a matter of debate, but is roughly 2,100 light-years. Over 3 degrees across (six times the angular size of the moon), its physical diameter is some 110 light-years. (Note: At this scale, the WFC3 image is just about 2 light-years across.)

Our current understanding of the Cygnus Loop is that a strong stellar wind from the pre-supernova star blew a large bubble or cavity in the interstellar gas into which the star exploded. The shock wave has expanded outward and is now in the process of encountering the walls of this cavity. But the cavity walls are not smooth and uniform, and may even be missing in some places, causing the current overall appearance of the Veil: bright regions are where the shock wave encounters

relatively dense material and faint regions are nearly devoid of material. The emission regions seen within the cavity (e.g., closer to the center) are thought to be portions of the outer shell seen in projection. The Hubble image, however, samples a portion of the outer limb or edge of the supernova remnant, where the shock front is being viewed from the side.



The Hubble field:

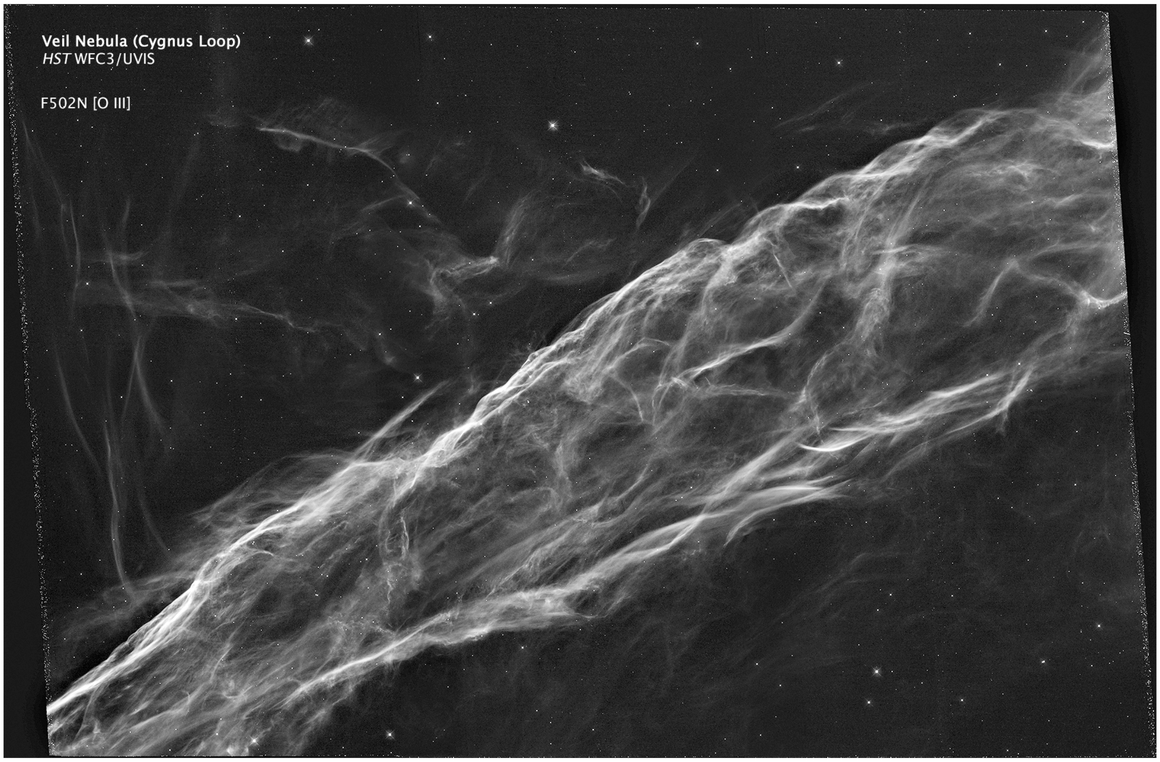
Even though the Hubble view incorporates six separate images from Hubble (in a 2x3 mosaic), it still encompasses only a tiny fraction of the outer shell, on the west side of the Cygnus Loop in a region known as NGC 6960, or more colloquially, the Witch's Broom Nebula or the Lace-work Nebula. The Hubble image shows an incredible array of structures and detail from the interaction of the supernova blast wave with varying density material in the cavity wall, seen as the main filamentary

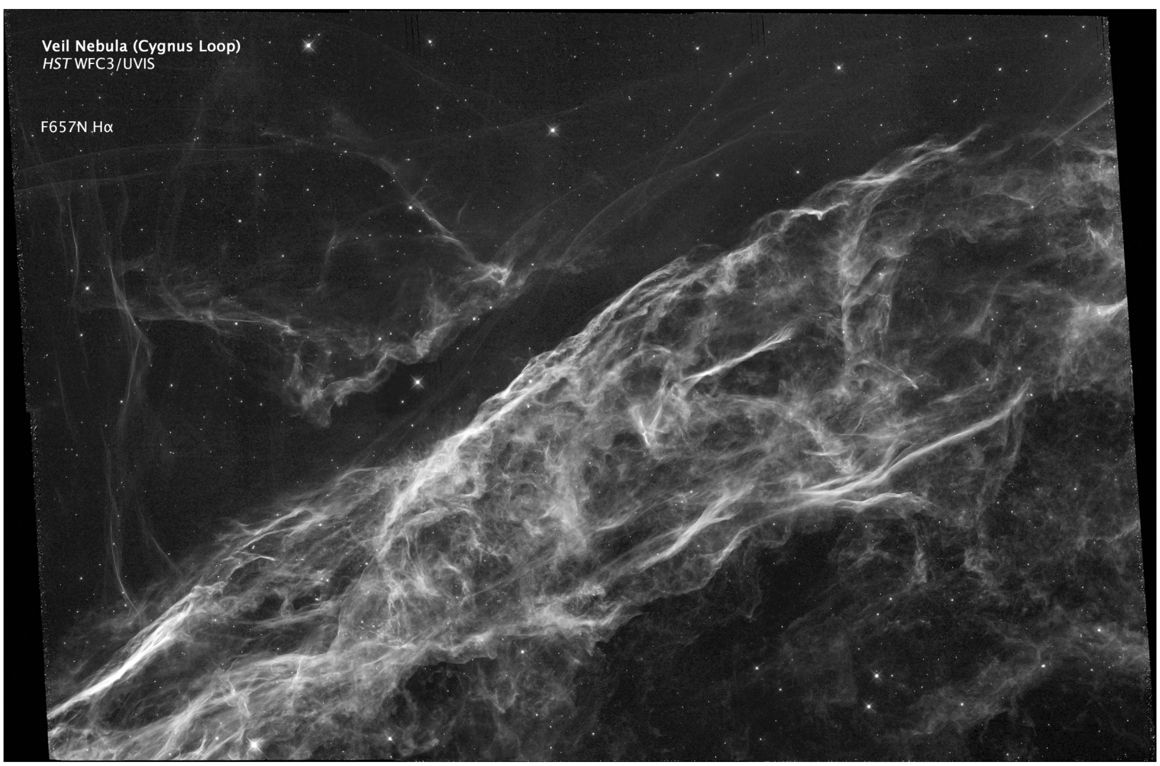
structure that traverses the image from lower left toward the upper right. The passage of the supernova blast wave heats and excites the gas, and as this gas cools down again it emits the light that Hubble sees.

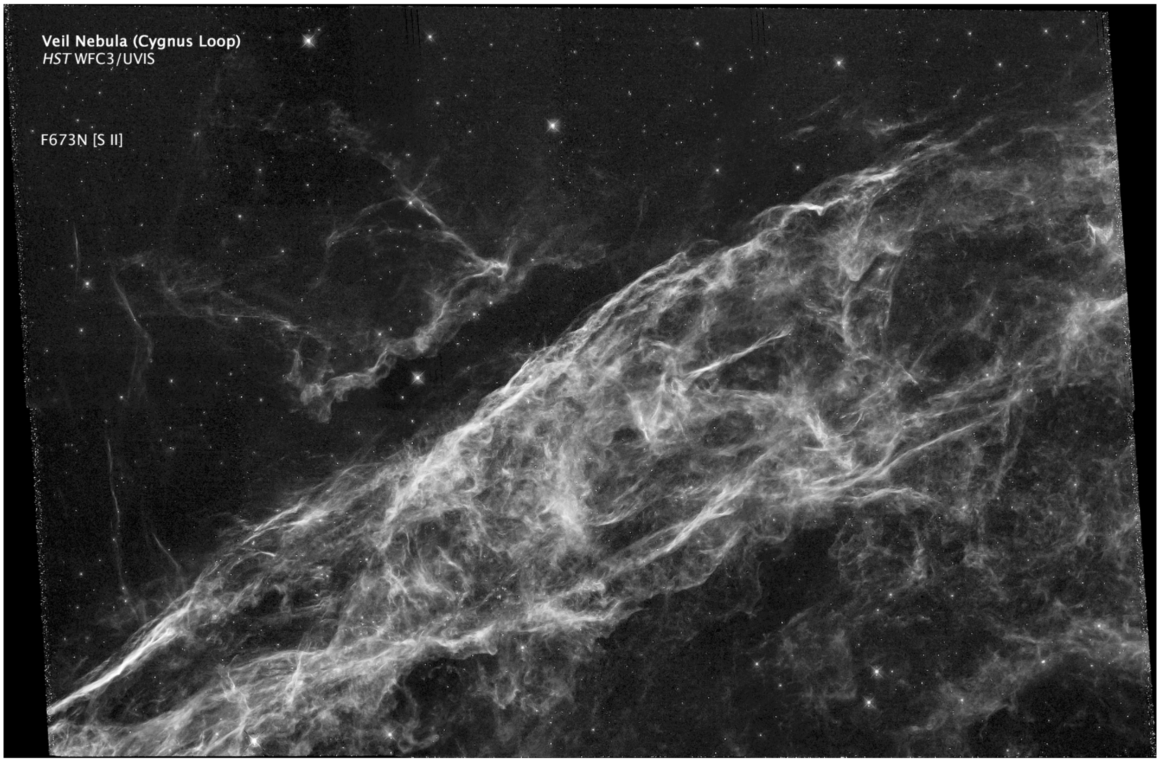
As shown in the release image, the blast wave is traveling from lower right toward the upper left; that is, regions at lower right are toward the interior of the shell, and regions toward the upper left are outside the main shell. The fact that some material is seen toward the upper left is due to projection effects, where some other portion of the cavity wall was thin enough that it has allowed the shock wave to "run ahead" of the main filaments. Another way of saying this is that much of the fainter emission at upper left is probably not directly associated with the bright filaments despite the appearance in the image.

What are the colors?

Three narrow-band filters have been used to sample the supernova remnant shock wave emissions. The F657N filter (red) is centered on the hydrogen Balmer-alpha emission line at 6563 Angstroms, the F673N filter (green) sees the light from once-ionized sulfur atoms (two lines at 6717 and 6730 Angstroms), and F502N (blue) sees emission from twice-ionized oxygen atoms (emission at 5007 Angstroms). However, even though each of these colors arises from a different chemical element, *the variations we see here are not from varying chemical abundances with position!* (All of the gas in the cavity wall is very nearly the same chemical composition since it is interstellar gas, not the ejecta from the supernova.) Rather, the different colors are primarily showing us variations in temperature and density of the emitting material.


Veil Nebula (Cygnus Loop)
HST WFC3/UVIS
F502N [O III]


Veil Nebula (Cygnus Loop)
HST WFC3/UVIS
F657N Hα



Two other filters, F555W and F814W, primarily sample the emission from stars, which in this case are at varying distances both in the foreground and background along the line of sight.

What does it all mean?

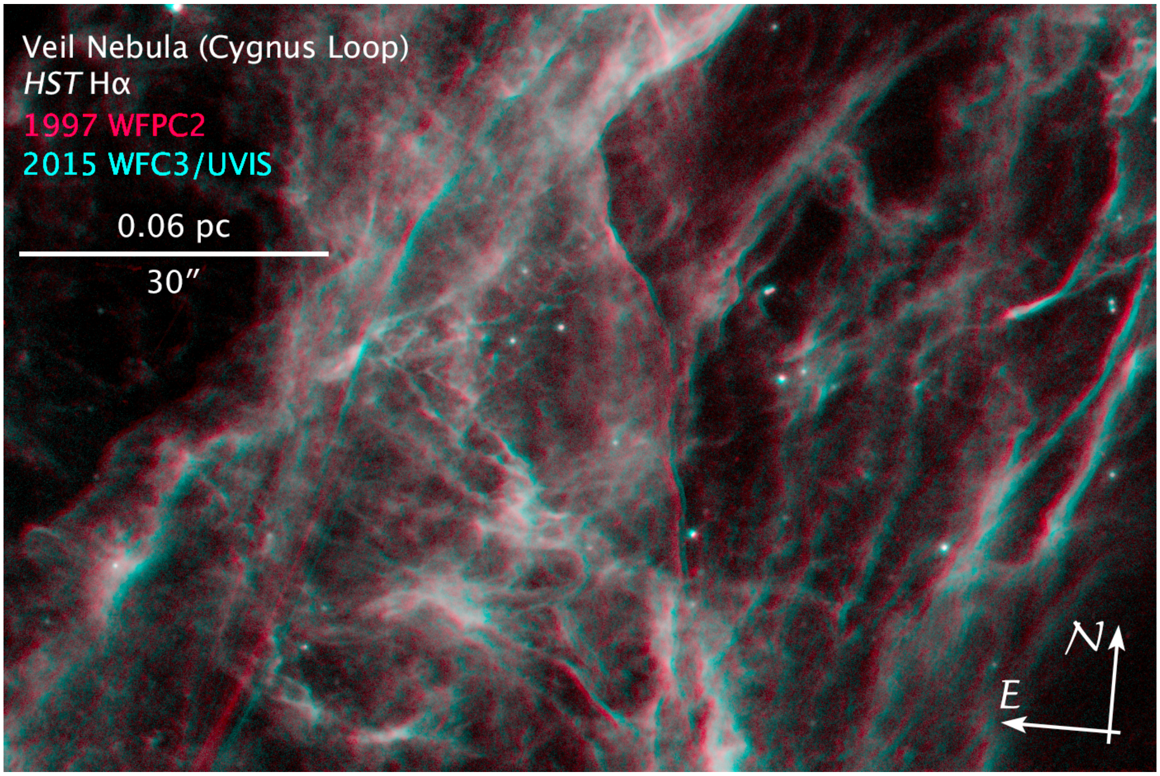
There are many things going on in this image and so the explanation is a bit complicated. Several things drive the overall appearance of the image: different physical processes from one place to another, varying temperatures and densities, different amounts of time since the emitting material was struck (and heated) by the blast wave, and of course the aforementioned projection effects, which operate on many scales.

To first order, since we are pointing Hubble at the edge of the supernova remnant shell, we are looking perpendicular to the motion of the shock wave, and hence are seeing tangencies to our line of sight. A good analogy would be to imagine viewing a wrinkled bed sheet from the side: there are large-scale tangencies from the overall sheet, and there are many smaller tangencies from the little wrinkles and wiggles in the surface of the sheet. Since in our case the sheet is emitting light, places where the sheet is seen edge-on get brighter, causing much of the structure seen in the image. Both large-scale and small-scale tangencies are visible throughout the overall chaotic structure.

The other dominant appearance in the image is the varying structure or appearance of the filaments in the different colors. (Astronomers call this the “morphology” of the filaments.) The blue (oxygen) emission seems generally smoother and more arc-like, while the green and most of the red emission looks more chaotic and “fluffy” (for lack of a better term). This is a real effect. The blue light arises in hotter gas that has more recently encountered the shock wave (and so still maintains the “shape” of the shock front), while the fluffy emission is cooler gas that was shocked longer ago and has had time to diffuse somewhat into the more chaotic structures. Of course, some of the emission is in transition between these two cases, providing the broad range of structures seen in the image. Given enough time, these fluffy filaments will cool down entirely and become invisible again.

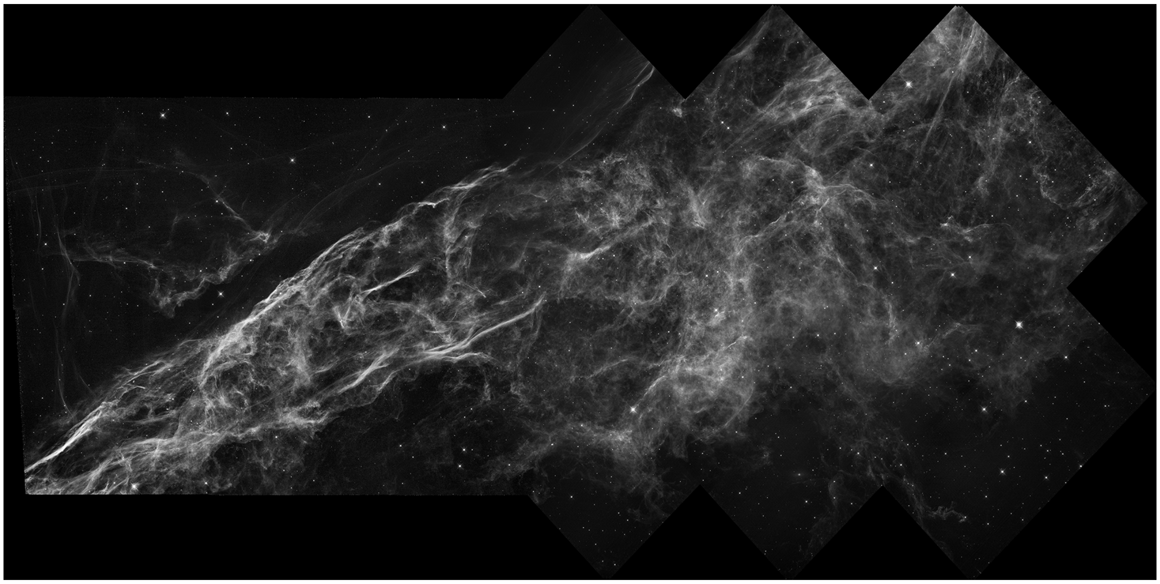
Careful inspection of the red emission shows that, in addition to the bright “fluffy” filaments, there are some faint but very thin, crisp-looking, red filaments. The cleanest example is just above center in the image, in front of the bright filaments, but other examples can be found even in projection against the bright emission. This faint hydrogen emission arises from a totally different mechanism. Rather than cooling gas well behind the blast wave, this emission arises from neutral hydrogen atoms being swept into the shock wave and being excited by particle collisions right at the shock front itself. This provides us with as close to a “snapshot” of the shock front as we could possibly want! Given enough time, the hydrogen will become ionized (so the faint red emission will go away), the gas will start to cool, and these filaments will become like the blue filaments in the picture. (And given even more time, they will look like the bright fluffy green and red filaments.)

Finally, a word about the fainter filaments at upper left, outside the main shell. As mentioned earlier, these filaments are from elsewhere along the line of sight and not directly related to the bright filaments that dominate the image. Some of the filaments are oriented almost perpendicular to the main shock direction, and may represent places where the primary shock has “reflected” off of a particularly strong density enhancement, causing secondary shocks to form in a different direction. However, many of the same things mentioned above, like crisper red and blue filaments transitioning to fluffier red and green filaments, can be seen in this sub-section of the image as well.



A detailed comparison of the Veil Nebula showing H-alpha emission from 1997 WFPC2 (cyan) and 2015 WFC3 (red) images.

We are lucky in that a portion of the new WFC3 view was observed using the WFPC2 camera back in 1997, some 18 years prior. Even at the tremendous distance of the Cygnus Loop, the motions of some of the shock fronts are visible over such a large time baseline. The motions are most obvious for none other than the faint, crisp hydrogen Balmer filaments just mentioned above. In the comparison image, one such filament can be seen as it meanders through the middle of the bright filaments that dominate the image. Almost certainly, this filament is just seen in projection against the bright filaments, and is really a portion of the shock front that is in the foreground or background of the bright filaments. These crisp hydrogen filaments arise from shock waves moving at about 400 kilometers per second (almost a million miles per hour!). The bright filaments arise from slower shocks in denser material, and so their offset over the same time period is less.



Mosaic of HST WFC3/UVIS and ACS/WFC images in the light of hydrogen (Hα)

The above image combines exposures from two of Hubble's cameras taken in the light of hydrogen (Hα), resulting in a wider mosaic. One can see how the character of the emission filaments changes from the portion imaged in WFC3 (relatively bright, crisp filaments on the left) to the portion imaged in ACS (mainly more fluffy, disorganized emission on the right). The WFC3 region has been shocked more recently and the shocked gas is cooling rather rapidly and dramatically, with relatively bright, structured filaments. The ACS region is material encountered by the shock earlier, and has had time to cool and begin to disperse, causing the fainter and fluffy appearance. There are relatively few edge-on filaments in the ACS region, implying that the emitting material really is more dispersed, and less like the "edge-on rippled sheet" model for the filaments in the WFC3 region.