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THE CRAB NEBULA: PUZZLES

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RESUMEN

Reportamos algunas observaciones recientes y pasadas de la Nebulosa del Cangrejo que enfatizan algunos enigmas viejos y nuevos alrededor de este bien estudiado, pero poco entendido objeto. Aún el tema más básico permanece abierto: ¿ está la nebulosa decayendo o aumentando su brillo? El origen del plasma magnetizado emisor de la radiación sincrotrón ha sido aparentemente resuelto con el descubrimiento del pulsar central, pero no es claro cual de las características dentro de la nebulosa corresponde a la onda de choque esperada. Hay ahora un sin número de opciones que van desde filamentos que sufren extrañas variaciones pero que no se mueven mucho, hasta los "nudos en emisión" recientemente descubiertos, adyacentes al pulsar. Todas estas estructuras están organizadas a lo largo del eje mayor de la nebulosa, el cual parece estar alineado con el eje de giro del pulsar.

ABSTRACT

We report on some recent and some past observations of the Crab Nebula which underscore some new and some enduring puzzles surrounding this well-studied but nevertheless enigmatic object. Even the most basic issue remains open: is the nebula fading or brightening? The origin of the magnetized synchrotron emitting plasma has apparently been solved following the discovery of the central pulsar, but it is not clear which if any features within the nebula correspond to the expected shock wave. There are now a plethora of choices ranging from the wisps, which undergo strange variations but do not move much, to the newly discovered "knot" of emission adjacent to the pulsar. All of these structures are organized along the long axis of the nebula, which seems to be aligned with the pulsar spin axis.

Key words: **IMS: INDIVIDUAL: CRAB NEBULA — STARS: NEUTRON — STARS: INDIVIDUAL: 0531+21 — SHOCKS WAVES**

1. INTRODUCTION

The Crab Nebula is arguably one of the most extensively studied objects in our galaxy. The supernova that gave birth was apparently observed in 1054 A.D., and presently the nebula and pulsar have been observed at every frequency in the electro-magnetic spectrum.

2. EVOLUTIONARY PUZZLES

Figure 1 shows an image of the nebular filaments reproduced from Hester et al. (1995b). We present it mainly to give the scale of the *HST* view. The labeled filaments are not discussed here. Given that the Crab Nebula has been observed for centuries and is a very *young* object, what do we know about the evolution. Specifically, is the Nebula as we now see it fading from view? This assumption would seem to be reasonable, but is not the result of any strong observational constraints. The same question goes for the central pulsar. These uncertainties were realized early on after SN1987A (Michel, Kennel, & Fowler 1987). There is surprisingly little firm data, although one would think that archival plates could resolve at least some of these issues. The two obvious scenarios are that the supernova declines until pulsar powering takes over and then the remnant fades along with the pulsar. But we do not even know that pulsars are fully "operational" immediately after

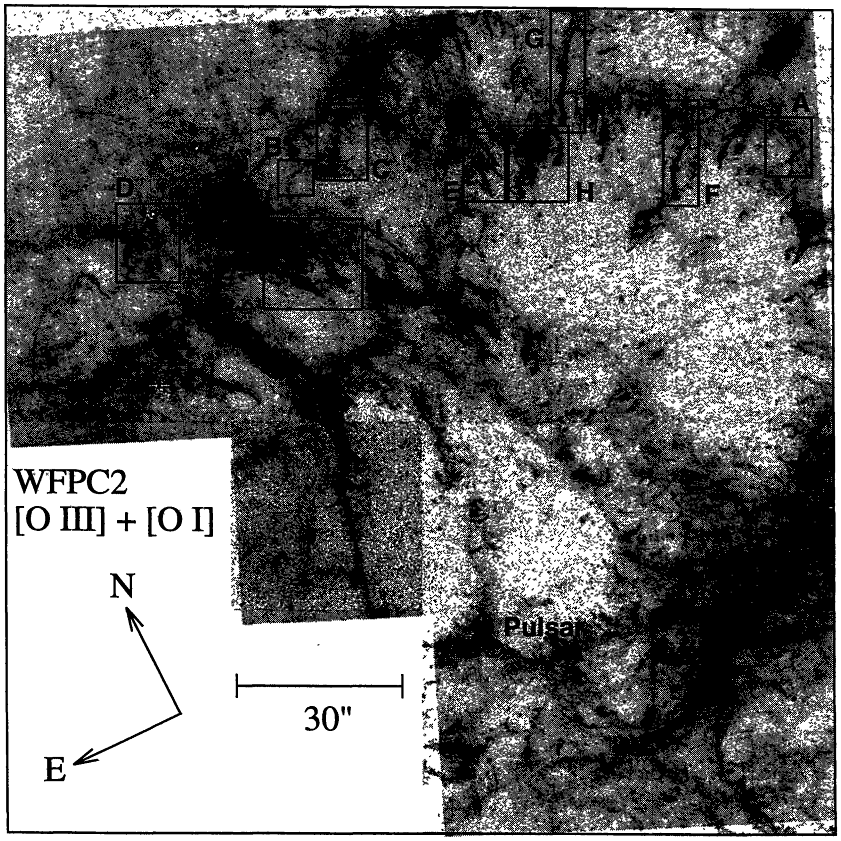


Fig. 1. *HST* WFPC2 image of the inner parts of the Crab Nebula. The pulsar location is essentially at the center and the frame extends to about 2/3 of the distance to roughly the "edge" of the nebula. This figure was taken from Hester et al. (1995b).

a supernova. For example, their huge fields might grow with time (Michel 1994a). It would therefore seem prudent to supplement our ignorance with another scenario, namely that the supernova might fade from view and then years later the nebula expands and *brightens* into view.

In the first scenario, "now" can be placed anywhere we want, since we are always on the declining side of the nebular evolution. But in the second scenario, it is not obvious where "now" might fall. We could still be on the brightening track, or we could be near the maximum, or we could again be on the declining side. The question is, ***why is not this known***? The system is less than a thousand years old, so a generic estimate of rates of change would be 0.1% yr^{-1}. Astronomers frequently quote stellar magnitudes to 0.01, or 1.0%. Thus determining changes at this level looks like "duck soup" (a strange idiom for "easy" that evidently came from the Marx Bros. movie of the same name). It is even easier if you use some estimates such as that by Pacini & Salvati (1983) where the optical emission should scale as the 9th power of the rotation frequency, which would immediately give 0.45% yr^{-1} decline in optical power. Yet people have been studying the optical emission from the pulsar for 30 years and the answer is ... nobody knows. (I confess that I have not exhaustively researched the staggering literature to make sure that there was not an abstract in some conference proceeding, but if there are such determinations, they seem not to be generally known.)

Careful measurements that have been done on the proper motion and Doppler shifts of the filamentary line emission, which together with the assumption that the nebula is a sphere gives the generally quoted distance of 2 kpc. In this connection, it should be mentioned that the nebula is obviously not a sphere but elongated along an axis about 45 degrees from North. It should also be noted that this distance is one of the calibration values used to determine pulsar distances in general!

3. SYNCHROTRON RADIATION

If one looks at the spectral power output (S) of the nebula, it is essentially a slowly falling one from radio to optical, at which point it changes to a much more steeply falling power-law (e.g., Figure 4-2 of Manchester & Taylor 1977). But synchrotron radiation from a single particle is a *rising* function of frequency ($S \approx f^{+1/3}$) until one reaches a cut-off frequency, after which the flux density plummets exponentially. Since the two look nothing alike, it is necessary to assume that one has a broken power-law spectrum of electron energies, since the cut-off frequency scales as

$$f_{\text{cutoff}} \approx \gamma^2 B, \tag{1}$$

where γ is the electron Lorentz factor and B is the nebular magnetic field. Since the luminosity from a single particle scales as

$$L \approx \gamma^2 B^2, \tag{2}$$

one can place the cut-off frequency in the optical and estimate the "equipartition" energy and magnetic field. Since neither synchrotron theory nor the nebula have changed *that* much since it was first done by Burbidge (1956), those estimates remain unchanged to this day and one typically finds

$$B \approx 10^{-3}\text{gauss}, \tag{3}$$

$$\gamma mc^2 \approx 10^{12}\text{eV}, \tag{4}$$

and

$$n \approx 10^{-5}(radio)\ \ to\ \ 10^{-8}cm^{-3}\ \ (X-ray). \tag{5}$$

The "age" of particles emitting at different cut-off frequencies is centered about the optical (about the age of the nebula), with the radio coming from electrons that live "forever" and X-ray emitting electrons having lives of months to years. Thus the break in the spectrum can be understood qualitatively as representing the accumulation of low energy (radio emitting) electrons until one gets to the optical and then the spectrum drops because those more energetic electrons are quickly exhausted. Of course, if the "radio" electrons *accumulate*, that suggests that the nebula might be *brightening*, unless the expansion has an overriding effect.

4. THE CENTRAL PULSAR

What did change from the time of Burbidge's calculations and the present was the discovery of the pulsar in the nebula. It had been recognized that there was no way that the magnetic flux in the nebula could have simply been packed into a single star prior to the supernova explosion. So at least this one puzzle has been resolved. We can estimate a magnetic field in the nebula in the following way. The period and rate of change of the period of the pulsar are easily measured from timing the pulses. Thus, equating the rotational energy loss with that of a magnetic dipole rotating at angular frequency Ω gives

$$I\Omega\dot{\Omega} = KB^2\Omega^4 \tag{6}$$

where K is a fixed product of fundamental constants, and I is generally of the order of 10^{45} g cm^2 based on neutron star structure models. One then obtains a value of 4×10^{12} gauss for the polar magnetic field of the pulsar. If we take this to fall off as a dipole out the "light-cylinder"/ wind-zone distance ($\equiv c/\Omega$), we have a reduction of about 3×10^6 to about a mega-gauss, and then out into the nebula, declining as $1/r$, by a light year corresponds to a reduction by the roughly 10^9 pulses in a year to 10^{-3} gauss. This is the same as estimated from equipartition, but the wind from a pulsar would provide this magnetic field within a single year, and much more so in 10^3 years!

The theories of pulsar winds are relatively primitive, starting with a model of my own (Michel 1969) wherein plasma is assumed to be dumped on rotating monopolar magnetic field lines and "slung" outwards by the resulting centrifugal force. The magnetic fields are forced to wind up into a spiral (falling off as $1/r$) and in the case of the Crab, the particle Lorentz factors would be of the order of 10^6. These numbers again seem broadly consistent with the Burbidge numbers. But the rate at which particles are expected to be injected from the Crab pulsar (see Michel 1991 for details of these estimates, or many other review articles) is only

$$\dot{N} \approx 10^{34}\text{particles/s} \tag{7}$$

and given that the above electron energy is essentially one erg, we see that we are about 4 orders of magnitude short of being able to directly power the nebula ($L \approx 10^{38}$ erg s^{-1}.) Kennel & Coroniti (1984) suggest that one can finesse this difficulty by assuming that 10^4 electron/positron pairs are emitted per current-carrying primary. This suggestion also solves a problem with "shocking" what otherwise would be a Poynting-flux dominated wind. Nevertheless, the issues of direct injection of energy in the form of leptons versus local acceleration (there must be magnetic energy being transferred back to particles somewhere: see Coroniti 1990 and Michel 1994b) remains open. In earlier days, it was argued that accelerating the electrons would have to accelerate protons and that would fill the nebula with cosmic ray energy that could not be dissipated. Possibly there are no ions where the reconnection takes place, but only pairs.

The bottom line, however, is the idea of a pulsar "wind" exciting the nebula was born and this idea continues to today.

Qualitatively then, a pulsar wind was expected to yield an invisible "hole" around the pulsar where the relativistic wind streams freely, then a shock (presumably an emission feature of some sort), and then an accommodating flow, which glows in synchrotron radiation.

5. SEEKING THE WIND

Figure 2 shows the same *HST* view as before but in the continuum.

We will compare the optical and X-ray, but first let us go to two figures of the *ROSAT* imaging of the Crab Nebula as provided by Bernd Aschenbach. The first image, Figure 3 shows a medium cut in the counting level. The points scattered over the frame are *not* noise. The X-ray sky is essentially black. Instead, these are X-rays scattered from the central source. These scattered X-rays make significant difficulties in determining fine

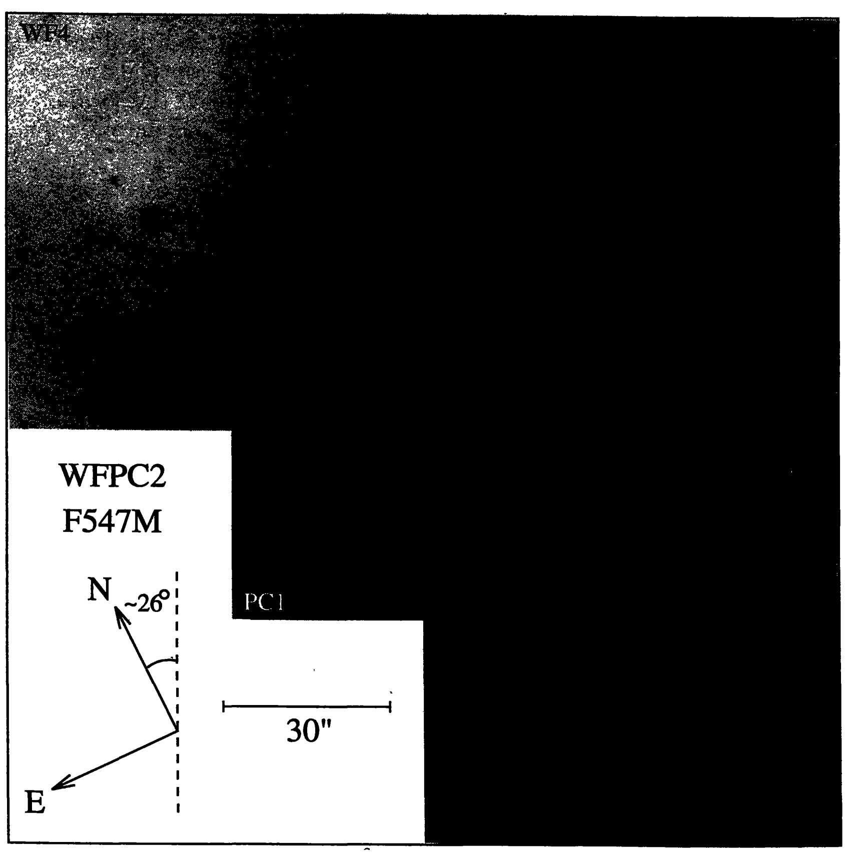


Fig. 2. Continuum *HST* image of the Crab Nebula. The pulsar is the lower right star of the two just to the right of the cut-out (see Figure 1). This figure was taken from Hester et al. (1995a).

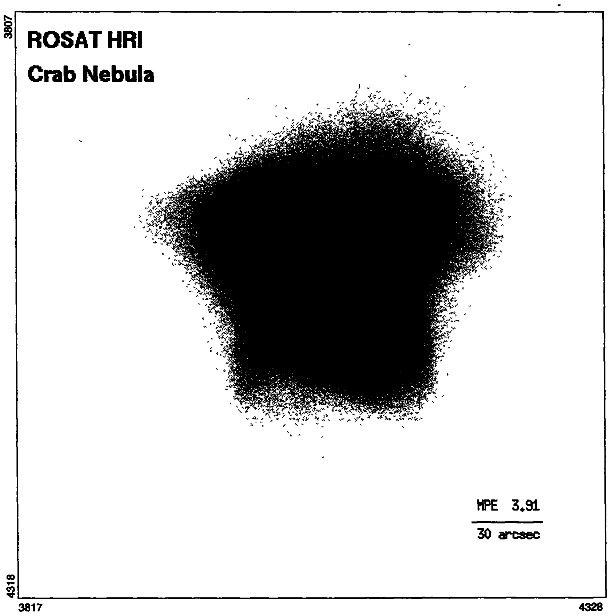


Fig. 3. *ROSAT* image of the Crab Nebula.

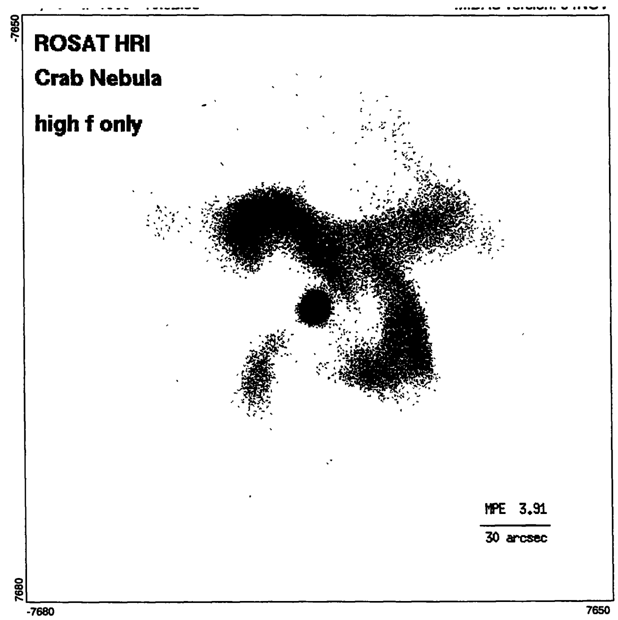


Fig. 4. *ROSAT* image of the Crab Nebula with low counting rates removed.

structure near the pulsar. The second *ROSAT* image, Figure 4 shows the central pulsar along with an elliptical "arc" of emission, interpreted on the basis of much older data as an expanding torus of emission, seen tipped up about 30 degrees (Aschenbach & Brinkmann 1975). Doppler brightening and dimming would account for why only the one side is readily seen. Note then the curved "jet" of emission coming down and what might be a broad counter-jet in the other direction. Strangely, this jet is easily seen in the *Einstein* data but was not reported. Note that the axis is aligned with the long axis of the nebula itself.

It is difficult to look at such data without immediately asking some obvious questions. Is this structure getting bigger, or what? The answers are not obvious; it could be growing with the overall expansion of the nebula or it could even be shrinking away *owing* to the expansion of the nebula. And are the X-rays fading or not as a whole?

If we compare the optical and X-ray, now pulling back and showing the entire nebula, we have the following as shown in Figure 5. The reproduction in sub-figure *c* clearly shows the very same "jet" in the optical as in the X-ray. There is just more clutter in the optical, and the jet appears more as a "shoulder" of emission paralleling the famous "bay," with a much less well defined boundary to the lower right. You will now be able to look at any optical continuum picture of the Crab henceforth and see the optical jet as well! It is difficult to see what people claim to be a "hole" near the pulsar; there is an arc of emission (the partial torus of Aschenbach & Brinkmann) to the upper right.

A careful study of the X-ray vs optical emission (Hester et al. 1995a) shows that (unsurprisingly) there is lots of optical emission where there is no X-ray. This makes sense given the short lifetimes of the X-ray emitting electrons. But the inverse also seems to be true! Yet another puzzle. Where do the X-ray emitting electrons go if not to become optical-emitting electrons?

6. POLARIZATION STUDIES

We have also studied the polarization properties of the nebula (Michel, Scowen, Dufour, & Hester 1991) by deriving the Stokes parameters and using them to produce images of the nebula in both unpolarized light and polarized light (i.e., visualizations that you cannot obtain at a telescope). Figure 6 shows the unpolarized light.

What exactly we are seeing is unclear because the synchrotron radiation is highly polarized. The simplest possibility is that we see unpolarized light because we are seeing emission from magnetic fields in different directions along the line of sight (combining light of two orthogonal directions of polarization cancels the

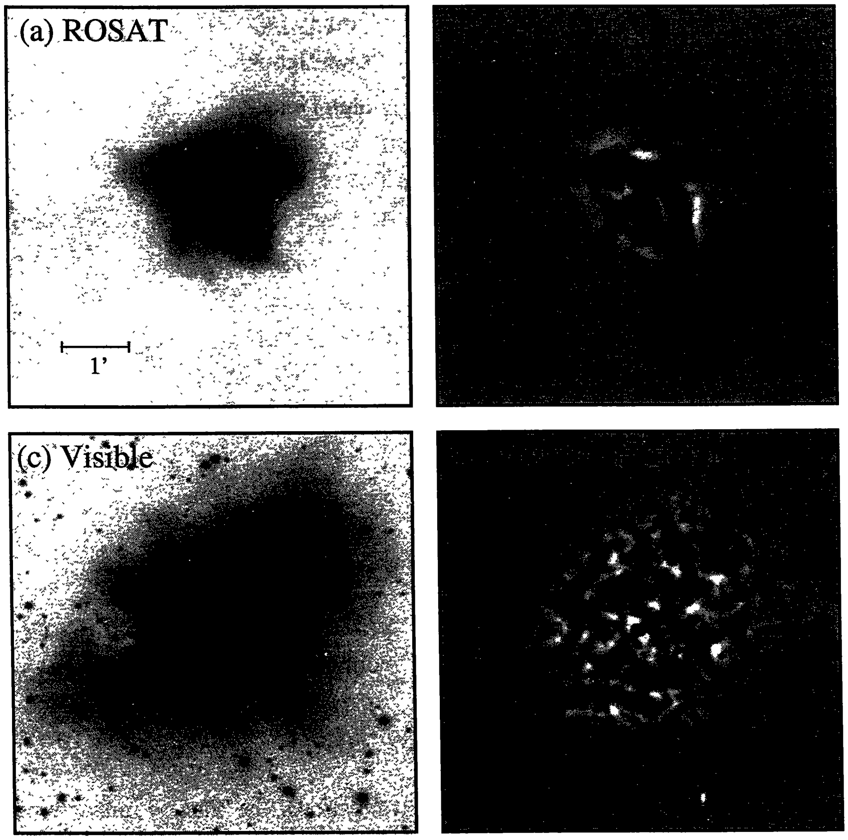


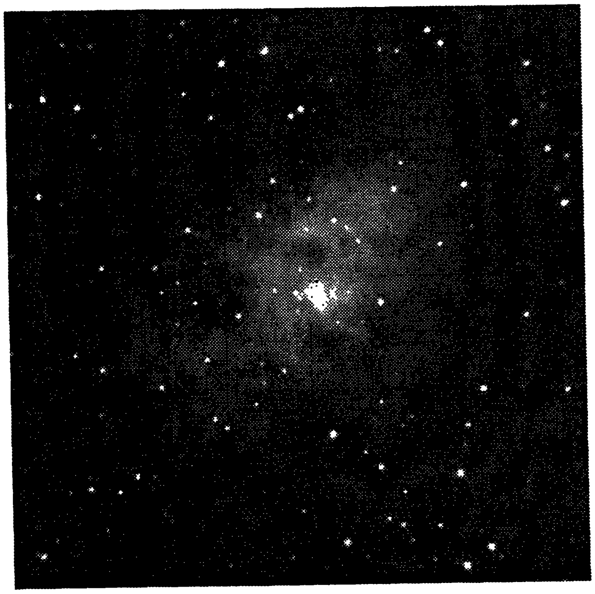
Fig. 5. *ROSAT* image (a) compared with the continuum optical (c), with high-pass versions of each. This figure was taken from Hester et al. (1995a).

polarization and leaves unpolarized light). Such twisting around of the magnetic field lines suggest external influences being important in the optical emission regions of the nebula.

Perhaps more interesting is Figure 7 which shows the startling "hourglass" structure at the center. This structure is more or less consistent with the Aschenbach & Brinkmann torus if the torus contains wound up magnetic fields from the pulsar (as expected from the wind models). If this wind has been shocked, the particles would have gained energy perpendicular to the magnetic field and they would preferentially be seen by us wherever the magnetic field lines lie in the plane of the sky. The locus of emission is then a line on the sky, perpendicular to the field lines and if you include some pitch-angle scattering, the line should widen into something like the hourglass seen. The orientations are not as consistent with the X-ray torus as they might be, however, and it may be that we are trying to force the proverbial square peg into a round hole. In any event, the continuum emissions seems to be confined into what seem like the filamentary cage of the outer nebula, whereas one could easily imagine a wind blowing out past debris, instead.

7. PUZZLE OF THE WISPS

The "wisps" arrayed about the pulsar have been a mystery for half a century or more, and numerous reports of *changes* in the wisps and nebula dot the literature, the most famous being a study by Scargle (1969), which unfortunately did not include any of the photographic data used in the analysis (the most recent, Hester et al 1995a, does however).



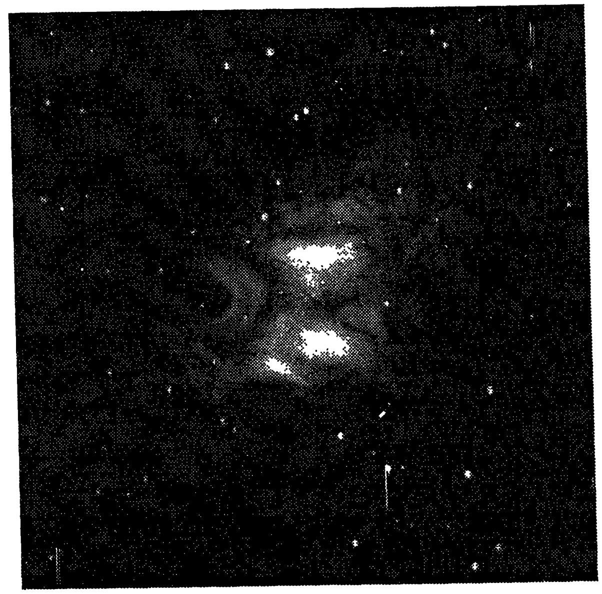


Fig. 6. Reconstructed Stokes parameters to give the unpolarized Crab visible light.
Fig. 7. Reconstructed Stokes parameters to give the polarized Crab visible light. The subtractions are difficult for point sources, so some stars still appear, although clearly surpressed.

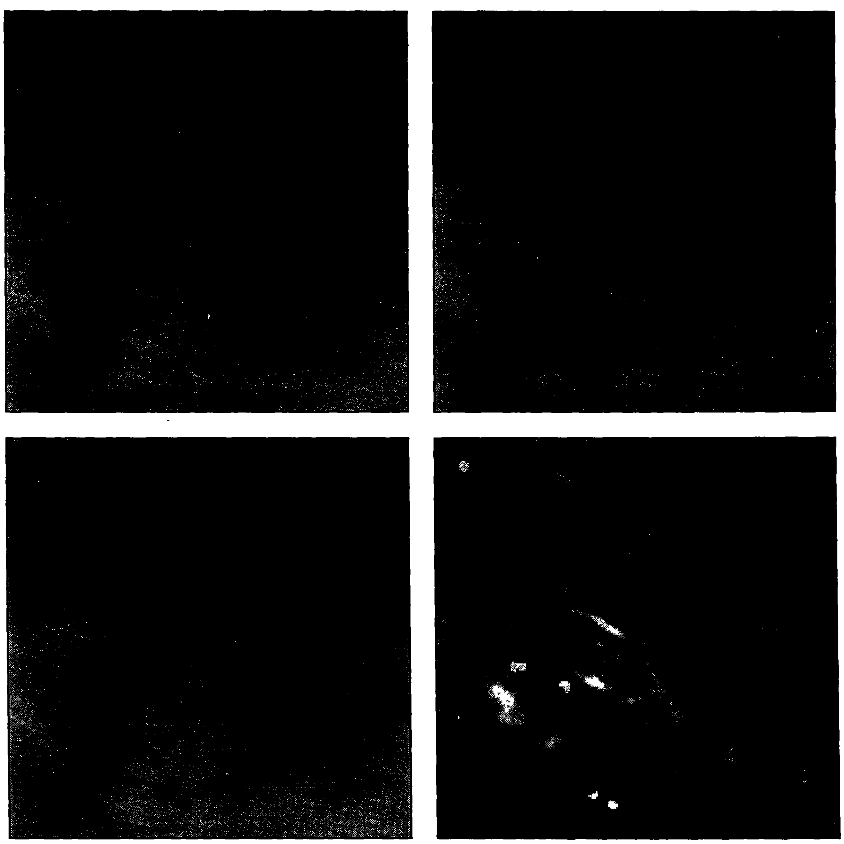


Fig. 8. Crab "wisps" (a) is *HST*, (b) is van den Bergh & Pritchet, (c) is *HST* resolution reduced to that in *b*, and (d) is the difference. This figure was taken from Hester et al. (1995a).

Figure 8 shows a close-up of the region around the pulsar. The association with the pulsar (as opposed to the field star to the upper left) is obvious, and a line perpendicular to the wisp features is exactly along the long axis of the nebula. One can readily see apparent changes in the wisps, particularly the one that is just to the North (up) of the pulsar and concave away from the pulsar. In the *HST* image it is brightest to the right of the pulsar, while in van den Bergh & Pritchet (1989), it is brightest to the left! Although there seem to be changes in the wisps, ***they stay in essentially the same places***! This behavior seems unreasonable from the wind point of view. Nothing very obvious can anchor features in place when the nebula is expected to be essentially empty (relativistic Alfven velocity plasma). The facile answer is that they are the expected shock wave (which should indeed be a more-or-less stationary feature). But they do not look in the least like shock waves.

A typical astrophysical shock wave is usually found at the far end of a jet from a source, yielding a typical bow shock, ***shaped*** like a bow. But there are numerous wisps, so they cannot all be shocks. Moreover, the "jet" seen in the X-ray does not itself seem to terminate in a shock. So our promising "wind" paradigm does not seem to fit especially well with what we are seeing. In fact, if we did not have this paradigm in the back of our mind, we would probably classify the wisps morphologically as some sort of clouds lit up by a precessing beam from the pulsar.

An interesting new idea has been forwarded by Gallant & Arons (1994) in which they interpret the wisps in terms of the ***structure*** of a collisionless shock. Often, spacecraft observations of collisionless shocks show a shock-like jump (in density, say) but followed by a series of oscillations after the jump. Numerical simulations show these oscillations to be due to ion cyclotron motion, which remains coherent for some time. Thus a series of wisps might be expected if the ion cyclotron radius was comparable to wisp displacements. Unfortunately these

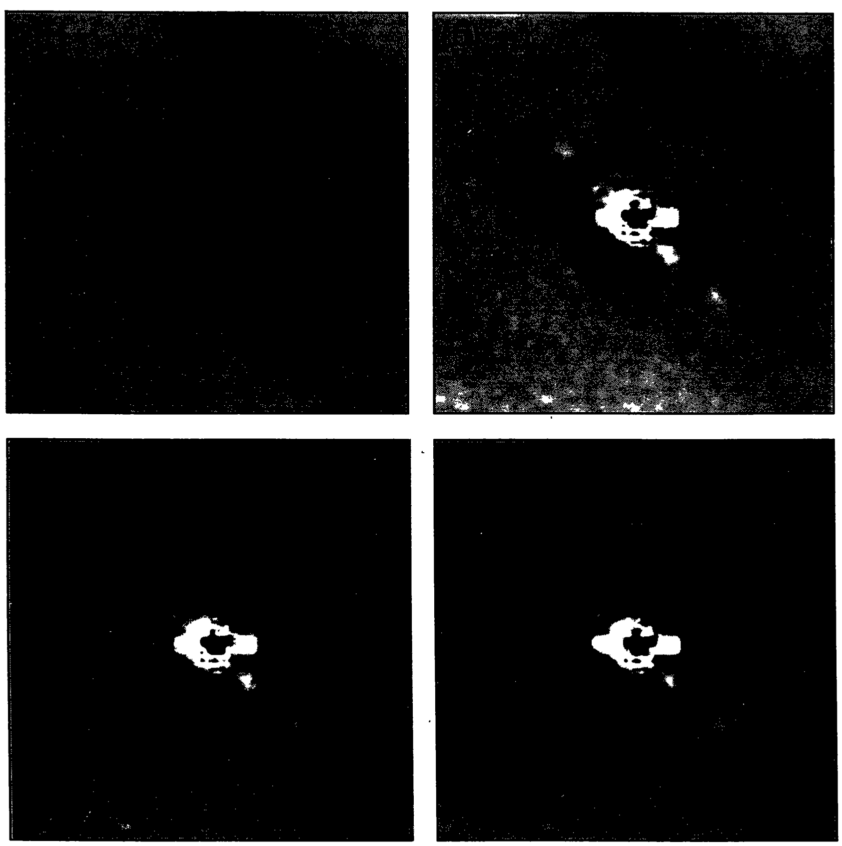


Fig. 9. Close up of the pulsar showing the knot of emission to the lower left (a). Attempts to remove the pulsar (b) show an elognated emission (c). A weak (20 times) counter knot, simulated in (d), would have been seen. This figure was taken from Hester et al. (1995a).

are huge macroscopic distances even without possible projection effects. Thus "nominal" parameters required are something like Fe-ions, with Lorentz factors of $\gamma \approx 10^6$ and $B \approx 10^{-5}$ gauss. The magnetic field alone is two orders of magnitude (three at this proximity to the pulsar) lower than expected. And how Fe-ions might gain *the same* Lorentz factor as the electrons is totally unclear (the same *energy*, yes, but not the same Lorentz factor). Using the convention estimates leads to shock structure far too fine to be resolved.

8. PUZZLE OF THE KNOT

Making one more zoom in to the pulsar, Hester et al. (1995a) report the discovery of a knot of emission that is again along what we might now call the "standard axis" of the system. Figure 9 shows this feature below and to the left of the pulsar. The concave wisp discussed earlier can be seen running along to the upper right of the pulsar. This knot is far too close to the pulsar to be the long sought shock wave, unless of course we are completely wrong about the nature of the pulsar wind. This knot could be dismissed as a star, but it is right on the standard axis and seems non-stellar (elongated). Ironically, the knot seems to be *just* faint enough that it would not have been seen using traditional photometry or stroboscopic viewing of the Crab (e.g., Miller, Wampler, & Scargle 1969) to pick the "off" phase of the pulsar.

9. CONCLUSIONS

HST observations of the Crab will be renewed later this year, so we will be able to find out if the knot is a transient feature or fixed to the pulsar, and hopefully we will be able to dissect details of how and where the wisps change with time as a clue to what they are.

But the issue of making traditional astronomical measurements to find even the *sign* of evolutionary changes to the Crab remains open. Magnitude determinations for the pulsar's stellar image seem straightforward. Determinations of the changes in the continuum over time are clearly much trickier, but it is hard to believe that they are impossible! So far theorists have been able to get away with just about any assumption they liked concerning the Crab Nebula, but if they had to explain why it was, say, fading in the radio while at the same time brightening in the optical, we would have much more physically interesting models of this curious object.

Much of the work reported here has been that of collaborators and co-authors of whom I would like to recognize J. Hester, P. Scowen, B. Aschenbach, and R. Dufour. One might also acknowledge the pioneers such as L. Woltjer, F. Zwicky, W. Baade, R. Minkowski, and many many more.

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