The Coolest Hot Cloud on the Southern Sky - The Southern Coalsack
by
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Things aren't always as they appear. That's true in every day life and in astronomy, both. Serendipity can reveal new insights that can send your research in a totally different direction – specifically, the discovery that an interstellar cloud selected to be cold and quiescent, ends up being a very violent place and potentially one of the best areas to study, in detail, the early processes leading up to the formation of new stars, and the interaction between hot plasmas and cold gas.

A number of years ago, some colleagues and I started a project to use the Hubble Space Telescope (HST) and the Far Ultraviolet Spectroscopic Explorer (FUSE) satellites to study the outer layers of cold interstellar clouds. As our first step, and considering how hard it is to get time on those facilities, we went looking for the very best clouds to include in our target list. We wanted near-by, cold, isolated clouds that weren't too disrupted by the formation of hot stars in their vicinity, preferably ones that had already been well-studied from the ground so that we could get as much background information as possible. We quickly settled on the Southern Coalsack as one of our target clouds, based on our criteria and the information available in the astronomical literature.

The Coalsack is a prominent dark area offset against the backdrop of the southern Milky Way, located next to the Southern Cross and the Jewel Box star cluster. On a dark night, it is – at least in my somewhat biased view – one of the most beautiful naked eye objects on the southern sky. Photographs of the region (see Figure 1) don't do the nebula justice, since to show detail they tend to be too "deep" and therefore show more stars than you see with your naked eye. On a clear, moonless, night you can easily understand how the cloud got its name.

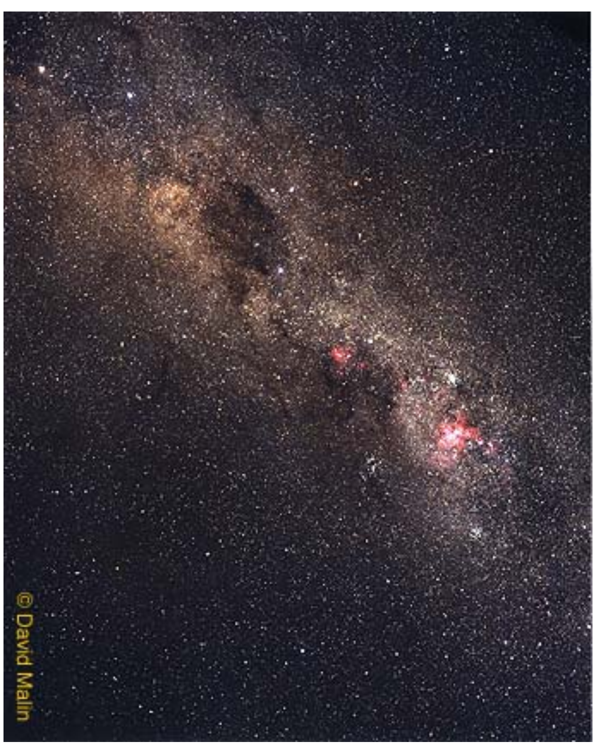


Figure 1. The Southern Coalsack stands out as a dark patch (upper left) against the diffuse light of the southern Galactic plane. Long-exposure images, like this one by David Malin, while beautiful, do not do justice to the visual impact of the cloud, since they show much fainter stars than the naked eye would pick up thereby lowering the contrast between the diffuse Galactic light and the deep darkness of the Coalsack. Note the Southern Cross just to the right of the cloud. (Photograph by David Malin)

Many studies have shown that the Coalsack is located about 600 light years away with little other interstellar material nearby, either in front of, or behind it. An important consideration for observing the gas in the cloud using ultraviolet spectroscopy with the two satellites were the fair number of hot stars in the region behind the cloud, which are closer than the next major layer of interstellar material in the so called "Carina spiral arm" at a distance of about 3000 light years.

Microwave observations of the carbon monoxide (CO) molecule told us that the cloud is dense and cold, while the detection of several spectral lines from easily ionized atoms, including neural potassium, told us that the cloud (or, as it turns out, the inner parts of it), could not be exposed to very energetic radiation, which would have ionized those "fragile" atoms.

In 1997 we submitted the first request to the FUSE mission to observe the molecular hydrogen (H_2) absorption caused by the Coalsack toward background stars. We were careful in our selection of the stars to be observed, choosing only those in the distance range such that they would only probe the gas in the Coalsack cloud. After the launch of the FUSE satellite in June 1999, we started receiving data from our observations. When we reviewed the spectra we soon noticed that there was a spectral line at 1032Å, which we had not expected to see: that of five times ionized Oxygen – or in astronomers' lingo: O VI (neutral oxygen is designated O I). This ion is generated at a temperature of about 300,000K and so is not expected to be associated with dark, cold interstellar clouds. Obviously, this surprised us quite a bit. To understand what was going on, we started systematically analyzing the FUSE O VI observations, re-scanning the existing literature and looking through the archives of other space missions.

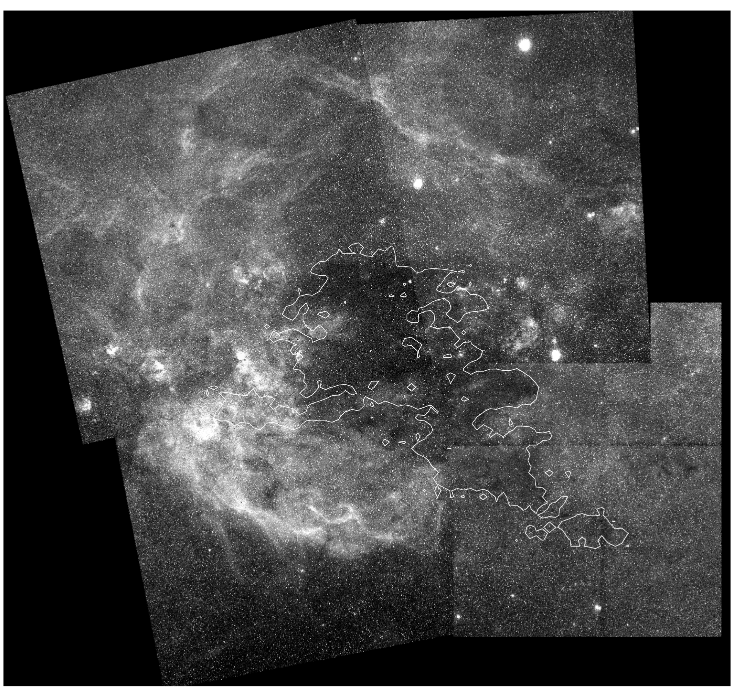


Figure 2. As noted by Andrew Walker and Bill Zealey at the University of Wollongong in 1998, the Coalsack is surrounded by an almost complete ring of emission in the Balmer alpha line of atomic hydrogen, as shown here. Balmer-alpha emission is characteristic of gas that has been ionized and is now recombining. (Figure by the author, based on individual Hα frames provided by W. Zealey)

As it turned out, in 1998, then graduate student Andrew Walker, together with his advisor Professor Bill Zealey of the University of Wollongong, had published an image of the Southern Coalsack taken to emphasize the emission-line radiation from the first excited state of neutral Hydrogen, Hα. Walker and Zealey saw an almost circular nebulosity in Hα, which they identified this as a supernova remnant. A reasonable conclusion, given the appearance of the object - except that it centered right on the Coalsack. Could there really be a supernova remnant right behind the center of the Coalsack? Because we had selected our FUSE stars to be located closely behind the cloud, we could rule that possibility out, since we knew that the distance to the gas containing the O VI ions is at the same distance as the cloud.

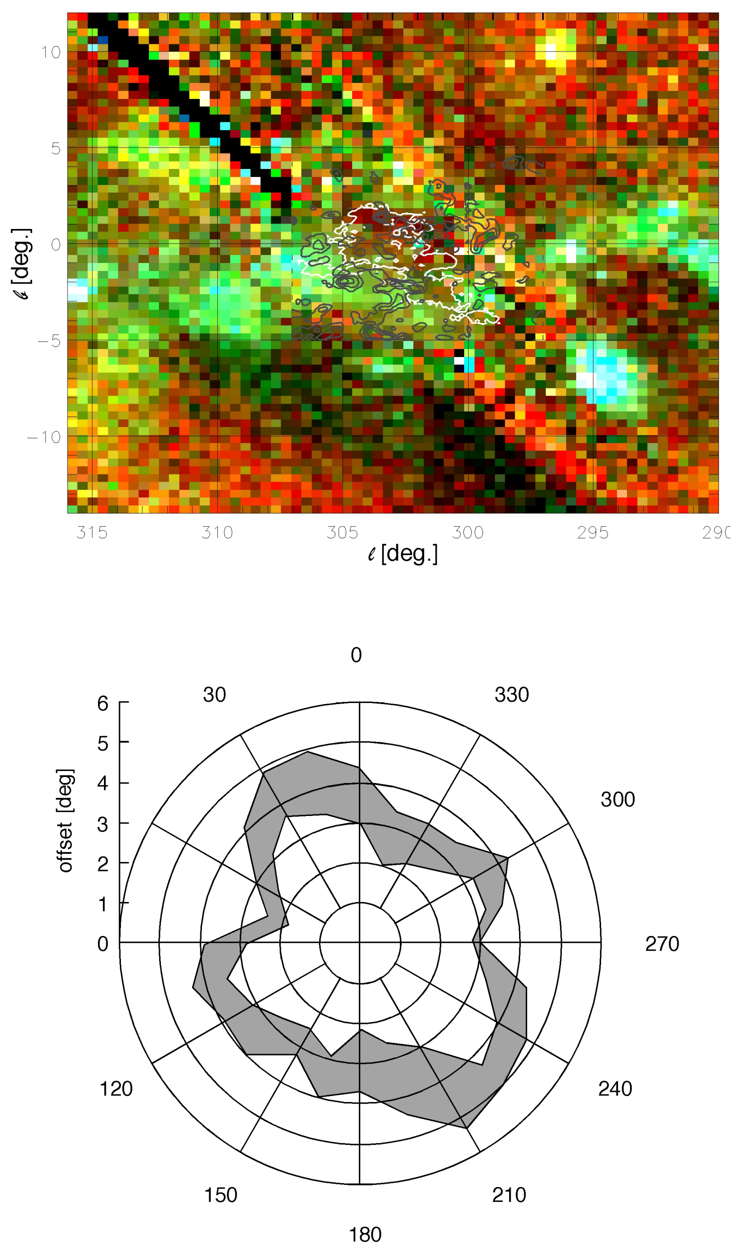


Figure 3. The Southern Coalsack (white contour) is surrounded by a bright X-ray halo and polarized radio emission (gray contours), in this false color image based on observations from the ROSAT satellite. Note that this image is oriented in Galactic coordinates. The black diagonal stripe is due to missing data in the ROSAT all-sky survey. (Adapted from Andersson & Potter 2010)

Because the Coalsack is located in the Galactic plane, there are also several unrelated X-ray sources in the field, but as the lower panel shows, a complete X-ray envelope can be traced around the cloud. That the halo is directly associated with the cloud is clear from the detection of absorption lines from O^{4+} in the gas.

Perusing the archives of earlier space missions we soon found the data in the "All Sky Survey" of the German/U.S. Röntgen – ROSAT – satellite. By superimposing the outline of the cold interstellar cloud, as traced by the CO emission, on the X-ray image of this region of the sky, we noticed that surrounding the cold cloud was a ring of bright X-ray emission. X-rays of the energy seen by ROSAT are usually generated by material at temperatures of about 1 million Kelvin, so here was a confirmation of our O VI results that some very hot gas was associated with the cold Coalsack cloud. But what was going on, and how could the cold cloud survive the contact of this very hot material? The first question was answered by some further literature searches, while the second was answered by our observation of the polarization caused by the cloud.

What could cause the outside of the cloud to become hot enough to ionize Oxygen four times and cause the gas to glow in X-rays? We felt that a supernova remnant (SNR) centered on the cloud was unreasonable as such a SNR should have disrupted the cloud. Further searches of the literature showed us that several shell-like structures had been seen in the radio lines of neutral hydrogen – the famous 21cm line – in the general area of the Coalsack, but on much larger scales than the cloud itself. These shells are usually called "Super-bubbles" and are due to the collective action of several supernovae and the stellar winds of hot young stars pushing the interstellar medium in front of them. Using the derived location of the stars and supernovae responsible for the "Upper Centaurus-Lupus Superbubble" and our best estimates of the energy and speed of the shell, we could show that the likely source of the heating the outside of the Coalsack cloud was that the surface of this Superbubble had passed over and then enveloped the Southern Coalsack cloud about a million years ago and the cloud is now fully enclosed in its hot interior.

This conclusion is supported by the discovery, from about the same time we published out FUSE observations, by Professor Charles ("Charlie") Lada's group at the Harvard-Smithsonian Center for Astrophysics, in the US, of a much smaller shell-like density structure, in the deepest, darkest core of the Coalsack, called "Tapia's Globule #2." Such shells are not stable and they are usually the result of outward movement, driven by the winds of forming stars. The only problem here is that no matter how hard people look, there are no newly formed stars in the cloud that could be responsible for pushing out such a shell. Professor Lada, and somewhat later, a group in France, suggested that this structure might instead be infalling and due to a pressure transient that passed over the cloud some 1 million years ago. The models by the French group predict that stars will form in Tapia's Globule #2 in about 10,000 years. "Instantaneously" on Galactic time scales. Finally, if you look at the CO image of the cloud, separated into narrow velocity bins, you see that there are coherent structures, which seem to flow away from the projected center of the Upper Centaurus-Lupus OB association and super bubble.

But how has the cloud survived from being evaporated if it's been hit and enveloped by a fast hot super bubble wind?

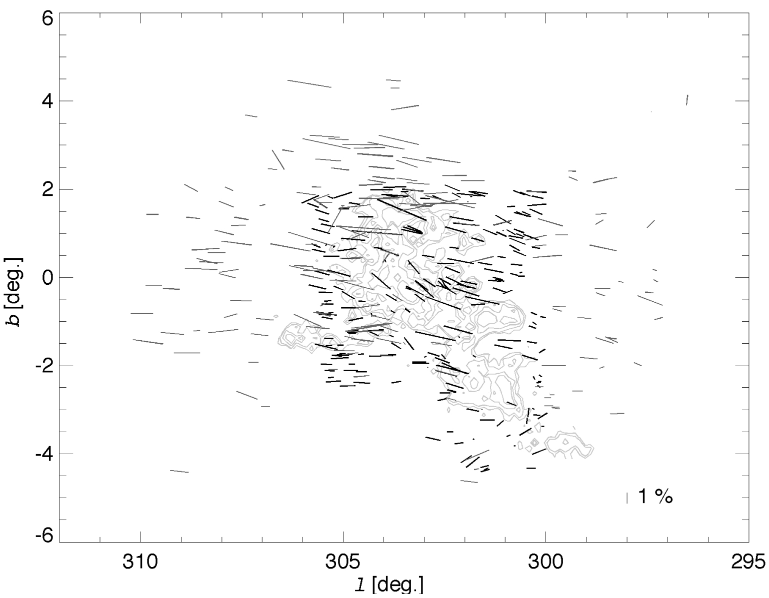


Figure 4. Passing through interstellar material, the light from background stars gets slightly polarized, due to irregular dust grains aligned with the magnetic field. This figure shows the polarizations measured for about 400 stars behind the Coalsack. The length and direction of each bar shows the amount of polarization seen (the bar at the lower right shows the length corresponding to 1% polarization) and the orientation of the polarization, respectively. The direction of the polarization vector traces the orientation of the magnetic field in that part of the cloud. The observations show a generally ordered field running from the upper left to lower right. The scatter around that average provides a measure of the strength of the magnetic field. (Adapted from Andersson & Potter 2005)

In the spring of 2000, our team was awarded a week of telescope time on the one-meter telescope of the South African Astronomical Observatory, using their polarimetry instrument. We measured the polarization caused by the Coalsack in the light of about 225 background stars. Analyzing those observations we realized that a quite strong magnetic field threads the cloud. Here, then, was a likely reason that the cloud persisted: as strong magnetic field can slow charged particles down quite substantially in moving long distance (of course, strong is a relative concept; the field in the cloud is quite weak, compared to what a common school bar magnet generates, but by interstellar standards, it is quite strong!). Once you know what to look for and where to look, you can see the effects of such hot and fast electrons in the radio emission, where they show up as polarized synchrotron emission (gray contours in Figure 3). Because the Coalsack straddles the Galactic midplane it wasn't obvious at first, but when Ramesh Bhat, of Swinburne University, and I, last year overlaid the cloud and the X-ray envelope on the synchrotron maps from the Parkes observatory, then, there it was: clearly associated polarized radio emission.

So, what have we learned? Looking at the scale of galaxies, particularly looking back to much younger galaxies than the Milky Way, we see that star formation often happens in intense bursts where the formation of stars in one cloud or region likely triggers further star formation in surrounding areas. But how such intense star formation can take place without disrupting the material is still unclear. Of course, even with the HST or the biggest ground-based telescopes we can't really see the details in such galaxies, so we need local "laboratories" where we can study the physics in detail. My colleague Hans Zinnecker, together with his former student Thomas Preibisch, looked at the earlier history of the general region that the Coalsack is part of and argued that the intense star formation we see today associated with the Opiuchus cloud was triggered by the effects of the stars that formed earlier in the Scorpio-Centaurus association. So, adding our chance discovery of the anomalous behavior of the Coalsack, we now have a near-by example of several generations of "triggered star formation," to help us understand the large scale phenomenon of star bursts: from the fully revealed Sco-Cen OB association, where very little remains of the parent cloud, via the intensely star forming clouds in Ophiuchus, to a cloud that is just about to start forming stars: The Southern Coalsack. Of course, much remains to be done, both in observations and modeling and, like all ongoing research, the picture might have to be revised. I currently have a martini riding on the observations we have pending at the Parkes observatory to independently measure the magnetic field in the cloud seeing at least half the strength we derived from the optical polarimetry. I'm trying to decide whether I'll ask for that martini shaken or stirred.

So, the next time you look up at that seemingly tranquil, dark patch called the Southern Coalsack, consider that it is actually a very hot and quite violent place, and that if you just hang around for another 10,000 years, you would see absolutely newborn stars in the cloud.

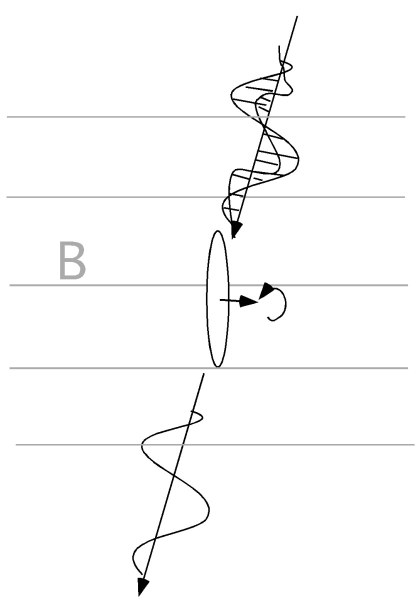
While Steven Stills had a point when he said that:

> "When you see the Southern Cross for the first time,
> You understand now why you came this way…"

Personally, as an interstellar-medium astronomer, I tend to side more with Glen Frey, when he noted that:

> "Just remember this my girl, when you look up in the sky
> you can see the stars and still not see the light…"

Then, I look just a bit east of Crux and make my reason for going observing in the southern hemisphere: that beautiful dark patch of sky called the Southern Coalsack.



Box: Why do magnetic fields cause polarization? Interstellar dust grains come in many sizes, shapes and compositions, of which some are elongated. Interactions with the surrounding radiation field will spin such grains up and when they encounter a magnetic field, they end up rotating across the direction of the magnetic field – like a cigar tumbling end over end. When the electromagnetic field of light encounters such aligned grain, the light oriented in the direction of the tumble of the grains gets slightly more absorbed by the grain that the orientation directed across the tumble, This causes a small difference in the transmission of the two components and thus a small polarization signal, typically of the order 1% for interstellar objects. This signal can be used to detect and characterize the presence of interstellar magnetic fields.