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Igor Krupnik, Michael A. Lang,
and Scott E. Miller
Editors

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Watching Star Birth from the Antarctic Plateau

N. F. H. Tothill, M. J. McCaughrean, C. K. Walker, C. Kulesa, A. Loehr, and S. Parshley

ABSTRACT. Astronomical instruments on the Antarctic plateau are very well suited to observing the formation of stars and their associated planetary systems since young stars emit their light at the wavelengths at which Antarctica offers the most striking advantages. Antarctic telescopes have already brought new insights into the physics of star formation and the molecular clouds where it occurs. During the International Polar Year (IPY), new sites will be opened up to astronomical exploitation, with the prospect of new capabilities in the drive to understand how stars and planets form.

INTRODUCTION

Stars are one of the main engines of evolution in the universe. They convert mass to light and hydrogen and helium into heavier elements; massive stars compress and disrupt nearby gas clouds by the action of their ionizing radiation and their stellar winds. However, the formation and early evolution of stars are not well understood: they form inside clouds of molecular gas and dust, which are opaque to visible light but transparent to infrared light and submillimeter-wave radiation. These wavebands are thus crucial to our understanding of the formation of stars: the young stars themselves radiate infrared light, which can penetrate the dark clouds, while submillimeter-wave observations can trace the gas and dust that make up the clouds.

ANTARCTIC SUBMILLIMETER TELESCOPE AND REMOTE OBSERVATORY OBSERVATIONS OF MOLECULAR CLOUDS

The main constituents of molecular clouds, hydrogen and helium gases, are effectively invisible to us: both molecular hydrogen and atomic helium have very few low-energy transitions that could be excited at the low temperatures prevailing in interstellar space. We therefore rely on tracers—gas and dust that are readily excited at low temperatures and readily emit at long wavelengths. The most basic of these tracers is carbon monoxide (CO), which is the most abundant molecule in these gas clouds after hydrogen (H_2) and helium (He).

N. F. H. Tothill, School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK; also Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA. M. J. McCaughrean, School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK. C. K. Walker and C. Kulesa, Steward Observatory, University of Arizona, Tucson, AZ 85721, USA. A. Loehr, Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA. S. Parshley, Department of Astronomy, Cornell University, Ithaca, NY 14853, USA. Corresponding author: N. F. H. Tothill (nfht@astro.ex.ac.uk).
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The lower-energy (low-J) transitions of CO emit radiation at wavelengths of 0.8–3mm, and are easily detected from high, dry, mountaintop sites in the temperate zones. At shorter wavelengths, the higher energy mid-J transitions can be detected only through a very dry atmosphere. The Antarctic plateau provides the largest fraction of such dry weather of any observing site in the world, and, sited at Amundsen-Scott South Pole Station, the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO; Stark et al., 2001) is designed to take full advantage of these conditions.

The mid-J transitions (from CO 4–3 up to CO 7–6) are particularly interesting for their ability to probe the physical conditions of the molecular gas from which they arise: in particular, they can only be excited in gas with density comparable to a critical density (about 10^4 molecules cm^{-3} for CO 4–3); emission in these transitions implies the presence of dense gas. By also observing the molecular clouds in lower-J transitions, AST/RO is able to trace the velocity structure of the gas clouds and to estimate the gas temperature, thus providing a suite of measurements of the physical conditions of the gas clouds where stars form.

Nearby Low-Mass Star-Forming Regions

All the nearest star-forming molecular clouds (within a few hundred parsecs; a parsec (pc) is a standard astronomical distance unit: 1 pc = 3.09×10^{16} m = 3.26 light-years) form low-mass stars. Because of their proximity, they subtend large areas on the sky (of the order of square degrees), requiring large amounts of time to map them properly. The Antarctic Submillimeter Telescope and Remote Observatory is very well suited to this task: its small mirror gives it a comparatively large beam, which, in turn, allows large areas to be mapped quickly. The highly transparent Antarctic atmosphere provides long stretches of very clear air in winter, which allows large blocks of time to be allocated to mapping these clouds at comparatively high frequencies. The clouds themselves are less dense and cooler than the giant molecular clouds that form the majority of stars, and many of the stars form in isolation, rather than in clusters. It is therefore often assumed that mid-J transitions of CO are not excited in these regions and are so difficult to detect that they no longer make good tracers. The AST/RO mapped large areas of two nearby cloud complexes, Lupus and Chamaeleon (named after the constellations in which they are found), in the CO 4–3 transition, finding significant emission. With a brightness temperature of the order of 1K, this CO 4–3 emission must come from molecular gas that is dense enough to thermalize the transition and warm enough to have a Rayleigh-Jeans temperature of a few Kelvin.

The Lupus star-forming region consists of a complex of molecular clouds lying about 150 pc from Earth, associated with a large number of young stars. The clouds are readily visible in optical photographs of the sky as clumpy, filamentary dark patches (Figure 1)—indeed, this is how these clouds were first discovered (Barnard, 1927). The Lupus complex lies to one side of the Scorpius–Centaurus OB Association (Sco-Cen), a huge collection of very massive young stars lying in the southern sky. On the other side of Sco-Cen, the rho Ophiuchi star-forming region displays clusters of massive young stars whose interaction with their natal molecular gas produces highly visible nebulae. By comparison to rho Ophiuchi, Lupus is quiescent—it is rather lacking in massive stars and has no large cluster, the young stars being much more spread out. One might therefore assume that Lupus would also lack the dense, warm molecular gas found in abundance in rho Ophiuchi.

However, the AST/RO data show detectable CO 4–3 emission throughout the Lupus clouds, with very strong emission in a few hot spots. By comparing this emission to the more easily excited ^{13}CO 2–1 (Figure 2), it is possible to estimate the physical conditions of the gas (Figure 3). The gas making up the bulk of the clouds is quite warm (probably >10K) and close to the critical density. The clumps within the cloud seem to be denser but not much cooler, and some are warm (around 20K). The data suggest that one of the hot spots in Lupus III is very warm (perhaps as much as 50K) but not dense enough to fully excite the 4–3 transition. The hot spot at the northwestern end of the Lupus I filament also appears to be warm and not very dense but has broader lines, implying more turbulent motion in the gas. While the elevated temperature in Lupus III can be explained by the proximity of the fairly massive young stars HR 5999 and 6000 (visible in Figure 1, lying in the dark cloud), there are no comparable stars near the end of the Lupus I filament. Clearly, the Lupus clouds show significant diversity in their physical conditions and, hence, in the environments in which stars are formed.

Being more easily excited, emission in the isotopically substituted ^{13}CO 2–1 line is distributed throughout the molecular gas and is less discriminating as a probe of the physical conditions of the gas. But because it is so widely distributed, it is an excellent tracer of the velocity field of the gas. The ability of AST/RO to map large areas allows us to fully sample the gas velocity field over degree-scale fields. Maps of the centroid velocity of the ^{13}CO 2–1 line show strong velocity gradients in several locations in the complex, usually

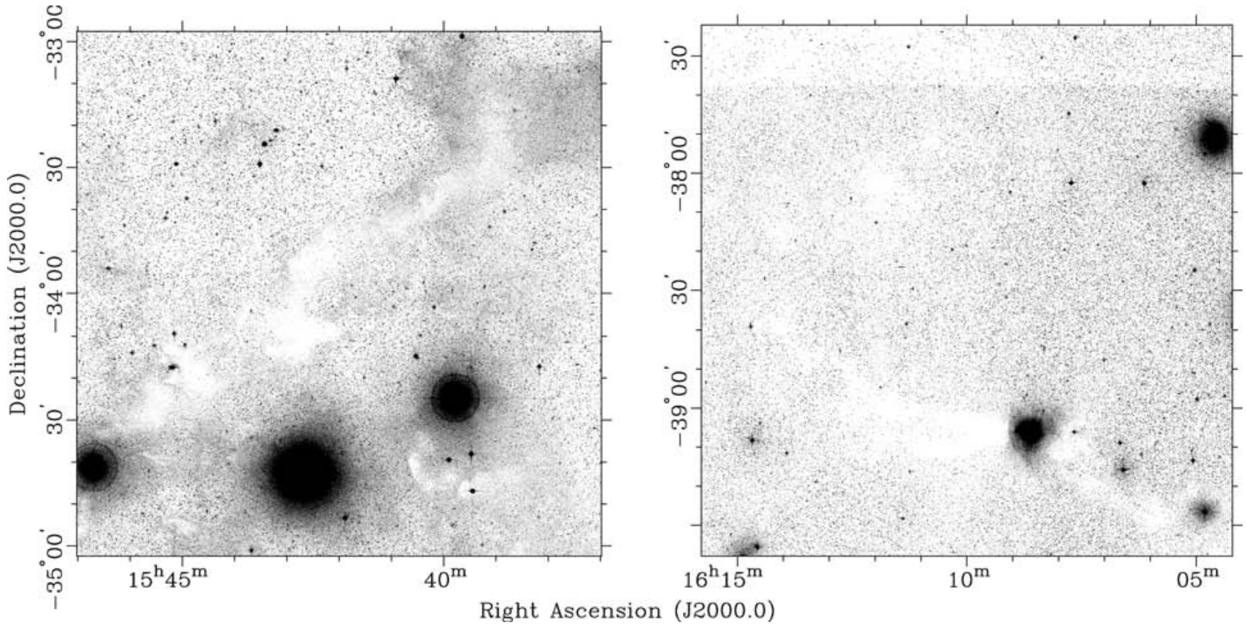

FIGURE 1. Two of the molecular clouds that make up the Lupus complex, visible as dark patches against the stars: (left) Lupus I and (right) Lupus III. The ridge in Lupus I is about 5 pc long. Images taken from the Digital Sky Survey (Lasker et al., 1990).

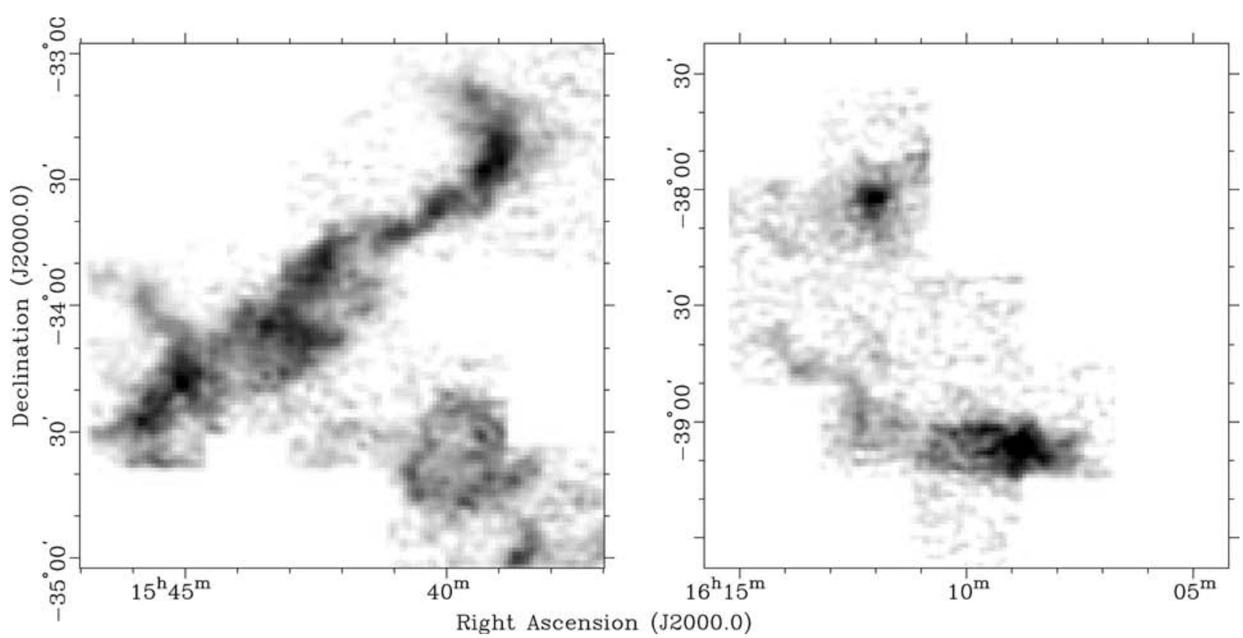

FIGURE 2. The same clouds as in Figure 1, mapped in the millimeter-wave emission of ^{13}CO 2–1. The isotopically substituted CO traces the dark cloud structure very well (N. F. H. Tothill, A. Loehr, S. C. Parshley, A. A. Stark, A. P. Lane, J. I. Harnett, G. Wright, C. K. Walker, T. L. Bourke, and P. C. Myers, unpublished manuscript).

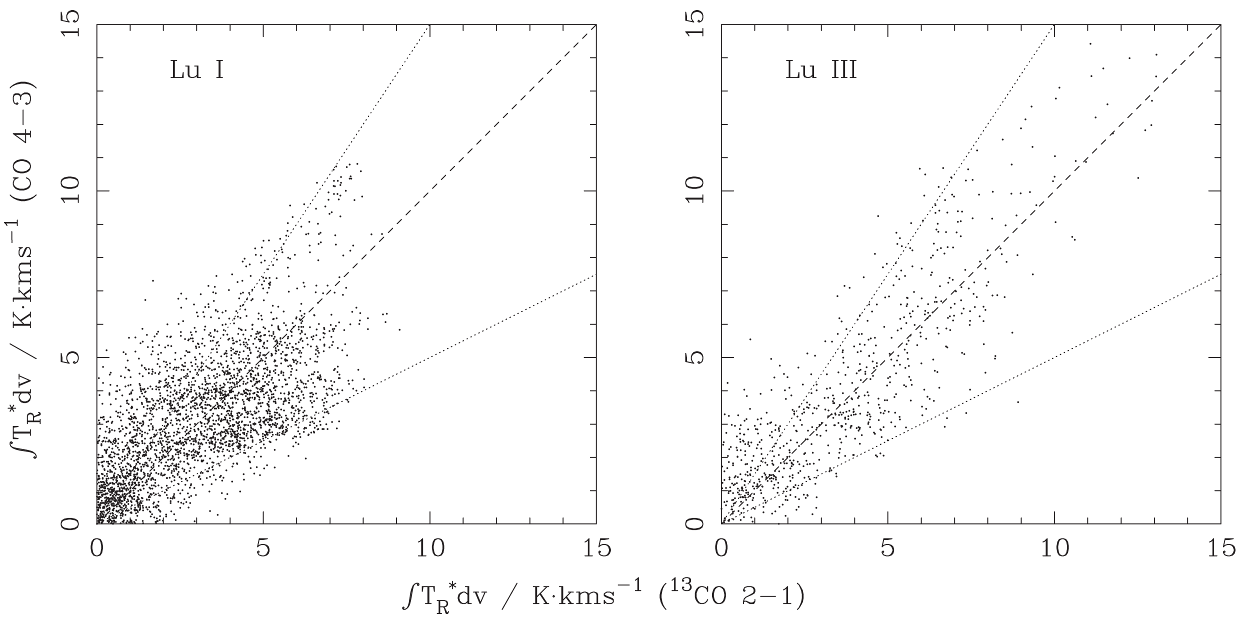

FIGURE 3. Comparison of CO 4–3 and ^{13}CO 2–1 emission from Lupus I and III clouds. The different physical conditions of the hot spots in the two clouds show up in the different distributions, but the bulk of each cloud is quite similar to that of the other (N. F. H. Tothill, A. Loehr, S. C. Parshley, A. A. Stark, A. P. Lane, J. I. Harnett, G. Wright, C. K. Walker, T. L. Bourke, and P. C. Myers, unpublished manuscript).

over quite small distances (about 0.5 pc), but in Lupus I, a different pattern emerges, of a shallow and rather uneven velocity gradient along the filament, coupled with a strong gradient across the filament. This gradient across the filament is coherent over at least 2 pc of the filament's length. The presence of such a large coherent structure in a region whose activity appears quite stochastic is remarkable; it may have arisen from external influences, presumably from Sco-Cen. The massive stars in Sco-Cen are quite capable of affecting nearby clouds; the rho Ophiuchi region on the other side of Sco-Cen is clearly influenced by the nearby OB association. There are some signs of a supernova remnant to the northwest of the Lupus I filament, which could have a strong dynamical effect on the gas.

NEW OBSERVING SITES IN THE ANTARCTIC AND ARCTIC

The factors that make the South Pole such a good site to detect the submillimeter-wave radiation from the clouds around young stars are likely to be found in many other locations on the Antarctic plateau and even at some sites in the Arctic. With the astronomical potential of the Antarctic plateau established, it is possible to evaluate other sites in the polar regions as potential observatories.

Projects to evaluate the potential of several polar sites are taking place during the International Polar Year: Astronomy from the Poles (AstroPoles) is a general program to study all the sites listed below, while STELLA ANTARCTICA concentrates on a more detailed study of the characteristics of the Franco-Italian Concordia station on Dome C.

The meteorology of Antarctica is dominated by the katabatic flow, as the air loses heat by contact with the radiatively cooled snow surface, loses buoyancy, and sinks down the slope of the ice sheet, leading to a downward-flowing wind. Most of the atmospheric turbulence is concentrated in a boundary layer between this flow and the ice, a layer which gets deeper farther downslope.

ANTARCTICA: DOME A

Dome A is the highest point on the plateau and has less atmosphere to get in the way than any other site. However, it also lacks infrastructure: in the absence of a year-round station, all instruments must be fully autonomous. Traverses to Dome A and astronomical site testing are being undertaken by the Polar Research Institute of China, in collaboration with an international consortium. This consortium, including Chinese institutions, the Universities of New South Wales, Arizona, and Exeter, and Caltech, is constructing and deploying the Plateau Observatory (PLATO), an automated unmanned site-testing observatory (Lawrence et al., 2006). One of the instruments on PLATO, PreHEAT, is designed to characterize the site quality at submillimeter wavelengths and to map the $J = 6–5$ emission of isotopically substituted ^{13}CO from massive star-forming regions and giant molecular clouds. It will be succeeded by the High Elevation Antarctic Terahertz Telescope (HEAT), a 0.5-m-aperture telescope designed to function around 0.2 mm wavelength. The HEAT will map the fine-structure emission from atomic and ionized carbon and nitrogen, together with CO 7–6, to trace the evolution and recycling of the interstellar medium in our galaxy. The prospects for PreHEAT and HEAT at Dome A are discussed in more detail in Walker and Kulesa (2009, this volume).

At the top of the continent, the boundary layer at Dome A may be only 3 to 4 m thick, which would make it much easier to place a telescope above the boundary layer, into what is likely to be very stable air with very good seeing. Other experiments on PLATO will test these predictions about the boundary layer at Dome A and sketch out its potential as a future observatory site.

Antarctica: Dome C

Dome C is significantly higher than the South Pole (around 3200 m elevation) and lies on a local maximum of the ice sheet along the ridge running through East Antarctica. It is likely to enjoy better conditions than the South Pole but not such good conditions as Dome A. Recent measurements (Lawrence et al., 2004) show the boundary layer to be about 30 m deep, with clear-air seeing above the layer estimated to be better than 0.3 arcseconds. Although Dome C probably enjoys better submillimeter atmospheric transparency than the South Pole, infrared astronomy seems more likely to be its greatest strength: the combination of excellent seeing, very little cloud cover, low thermal background (due to the cold air), and the presence of a year-round crewed station with strong logistical support makes it possible to build an infrared facility telescope with a primary mirror diameter of 2 m or more, which would be competitive with the largest telescopes elsewhere in the world (Burton et al., 2005). Detailed site testing at Concordia is being carried out by the IPY program STELLA ANTARCTICA and by members of the European Commission–funded network "Antarctic Research—A European Network for Astronomy" (ARENA). In the near future, this should lead to the construction and validation of a model of the boundary layer that allows telescopes to be designed to take advantage of the unusual conditions at this site. Two small telescopes are in the process of being designed and deployed to Concordia: Antarctica Search for Transiting Extrasolar Planets (ASTEP) is an optical time series experiment, designed to monitor the brightness of nearby stars and watch for the fluctuations as their planets transit. The International Robotic Antarctic Infrared Telescope (IRAIT) is a 0.8-m-aperture infrared telescope to carry out wide-field infrared surveys and to test the site characteristics for a larger infrared telescope.

Greenland: Summit

The atmosphere above the Greenland ice cap in winter is also dominated by katabatic flow. The peak of the ice cap (Summit station, at latitude 72°N) is therefore analogous to Dome A in Antarctica, albeit less extreme: lower (3200 m), warmer (about −42°C in good observing conditions), etc. Nonetheless, it should share many characteristics of Antarctic plateau sites, such as cold, dry, stable air. It has its own advantages: it is crewed year-round and access is easy in summer, possible in winter; it also has access to the northern sky, which is invisible from Antarctica. All these factors combine to give Summit excellent potential as an observatory site. There is also room for synergy with Antarctic observatories in order to cover more of the sky and to prototype and test equipment at a more easily accessible location.

Ellesmere Island

The northern tip of Ellesmere Island in Canada lies very close to the North Pole and thus offers at least one of the advantages of very high latitude sites, namely, the ready availability of 24-hour darkness with small changes in source elevation. Since this part of Ellesmere Island is rocky, with mountain peaks rising above the permanent sea ice, it is likely to have rather different meteorology to the smooth ice caps in Greenland and Antarctica. Automated weather stations have been placed on several candidate rocky peaks on the northern coast, and the first results of this basic site testing are expected shortly.

CONCLUSIONS

Understanding the process of star formation requires the observation of infrared light (to see the young star through the gas and dust around it) and submillimeter waves (to estimate the physical conditions of the molecular gas itself). Observations from the Antarctic plateau offer large advantages in both of these regimes, demonstrated by the AST/RO observations of nearby molecular clouds, which yield a picture of quite different molecular clouds: Lupus I has strong coherent velocity gradients and may have been externally influenced, while Lupus III has been heated by associated young stars.

During the International Polar Year, efforts to test the suitability of other sites for astronomy are under way: Concordia Station on Dome C is likely to be an excellent infrared site and is the best known. Other sites (Dome A, Summit, and Ellesmere Island) are at much earlier stages of characterization.

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