Harley examines how species-specific climatic tolerances, climatic niches, and species interactions drive species distributions, abundances, and species richness. Focusing on a predator (sea stars) and its prey (mussels and barnacles), he integrates information on changes in the prey and predator distribution between 1957 and 2010, a period during which the local climate warmed by almost 1°C. The author also analyzes predator removal experiments to elucidate species responses across a whole community.

Previous studies have either focused on specific taxa, localities, or period of time, or have been so general that many relevant macroecological details remained implicit. Harley overcomes many of these limitations by using a more comprehensive toolbox borrowed from both community ecology and macroecology. By analyzing the change in the amount of suitable habitat for mussels and barnacles due to climate change since 1957, combined with the experimental removal of the predator, Harley identifies responses of intertidal communities, including local extinctions, to different stress factors such as temperature increase and predator pressure. He further demonstrates that those changes have a substantial impact on the composition and richness of communities of up to 37 intertidal species, which depend on the cool and moist conditions created by mussel beds, that is, on the microclimate induced by a dominant species in the community.

Imagine community ecologists moving away from small-scale, single-locality research and beginning to use Harley-inspired study designs at macroecological scales, with thousands of sites in different biomes across biogeographical regions (see the figure). If the resulting ecological data are combined with physiological and genetic data, such a framework could answer highly relevant questions on the physiological limits of populations and on the extant plasticity and genetic variation, helping to predict which species can adapt to a changing climate. Such research designs would further benefit from manipulative climate-change experiments across trophic levels. Imagine also macroecologists incorporating these insights into their models to move beyond statistical correlations (*13*) toward explaining biodiversity patterns by a mechanistic evaluation of processes across spatial and temporal scales (*14*). Such large-scale, interdisciplinary, and cross-scale approaches are needed to predict more accurately and precisely how biodiversity will respond to ongoing global climate change.

Such a change from the traditional research and funding structure in ecological disciplines, from small individual grants to large global consortia, is by no means trivial. It would require substantial, if not dramatic, changes in the distribution of funds, the criteria by which they are awarded, how researchers collaborate, and (not least) how scientific credit is partitioned between groups and individuals. It is time for ecologists to discuss the pros and cons of such changes, because moving in this direction will allow us to better cope with the research challenges of our changing world.

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ASTRONOMY

Cosmic-Ray Origins

W. Robert Binns

The detection of distributed, high-energy gamma-ray emission points to cosmic-ray acceleration in a superbubble.

The origin of cosmic rays has been a mystery since it was conclusively shown by Victor Hess (*1*) that ionizing radiation impinges on Earth from space, and subsequently shown by Arthur Compton (*2*) that this cosmic radiation is primarily composed of charged particles. Since that time, there has been great interest in understanding the origin of these cosmic nuclei accelerated to nearly the speed of light—identifying the source of the material that is accelerated, the nature of the accelerator, and the mechanism by which the source material is injected into the accelerator. On page 1103 of this issue, Ackermann *et al*. (*3*) report observations with NASA's Fermi Large Area Telescope that are directly related to the origin of cosmic rays. They identified distributed emission of gamma-rays over the energy range of 1 to 100 GeV in the Cygnus X region of the sky with a "cocoon" of freshly accelerated cosmic rays.

The direct measurement of cosmic rays—their elemental and isotopic composition, and their energy spectra—has also provided important clues to the origin of cosmic rays since they bear the direct imprint of their nucleosynthesis, injection, and acceleration. However, because our galaxy and all of space is riddled with magnetic fields, and because cosmic rays are charged particles, their arrival directions at Earth do not usually point back to their sources. By contrast, instruments that detect gamma rays do point back to the source where they are produced. Gamma-ray measurements can therefore indicate specific sites of acceleration, and in some cases can distinguish between electron and hadron acceleration processes.

The cocoon identified by Ackermann *et al*. extends ~50 parsec from the Cygnus OB2 association—a very large cluster of more than 500 stars, each with mass greater than 10 solar masses ($M_\odot$) (*3*) (called types O and B stars)—to γ Cygni, a young (age ~7000 years) supernova (*4*). Near γ Cygni is NGC 6910, an open cluster containing ~75 massive stars. The gamma-ray emission is most intense in Cygnus OB2 and γ Cygni. After subtraction of a modeled background emission spectrum, including the point source emission from γ Cygni, most of the remaining distributed emission extends along a line from Cygnus OB2 to NGC 6910, with peak emission coming from those stellar clusters. The morphology of the enhanced emission region is bounded by regions of 8 μm

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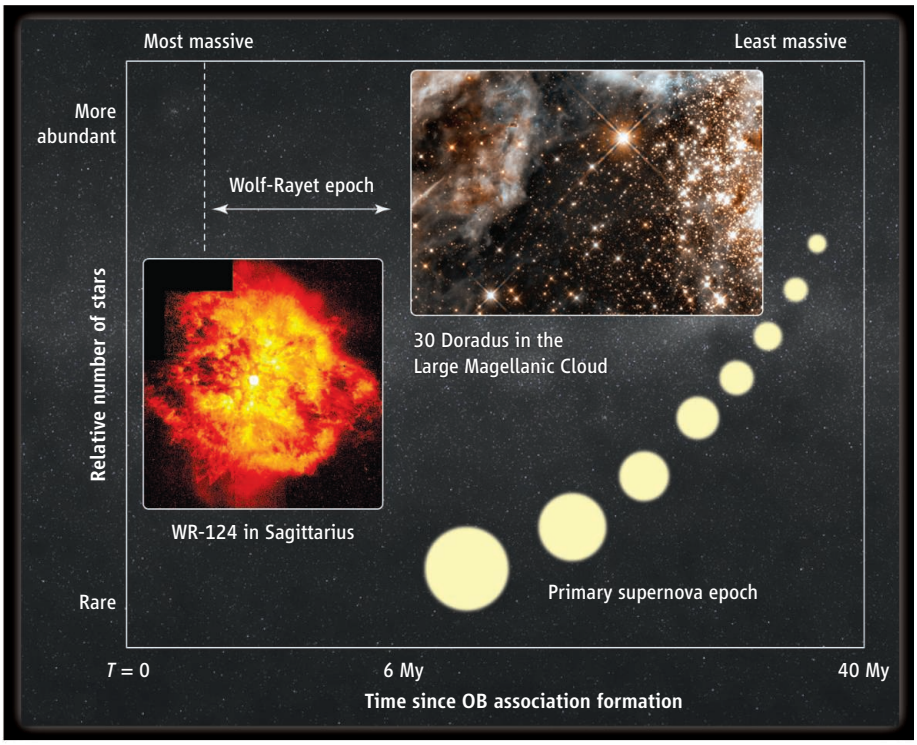

A history of massive stars. After formation of the massive stars, the heaviest of them (initial mass >40 $M_\odot$) burn their fuel most rapidly and have the shortest lifetimes (≤6 million years). Before their core collapse, these stars enter the Wolf-Rayet (WR) phase, during which they produce ferocious stellar winds and experience rapid mass loss (*14*). Lighter-weight massive stars have longer lifetimes; the least-massive star that can undergo core collapse (mass of ~8 $M_\odot$) has a lifetime of ~40 million years (My). There are many more lower-mass stars than highest-mass stars. During the first 6 million years, the high-velocity WR winds and supernovae shocks may accelerate cosmic rays, while during the remainder of the OB association lifetime, supernovae shocks are likely the primary accelerator.

infrared emission, which results from compressed ionized gas that forms the edge of the Cygnus superbubble and corresponds to the cocoon. Ackermann *et al*. divided the cocoon into subregions and found that the energy spectra were consistent, an unlikely result if the emission were from multiple individual sources. The emission spectrum is such that it could result from either proton or electron acceleration. However, the gamma-ray flux measured by Milagro in this same region at higher energy (~10^{13} eV) (*5*) is inconsistent with electron emission, thereby favoring proton acceleration. Either way, the gamma-ray spectrum presents compelling evidence of freshly accelerated cosmic rays within a superbubble.

This gamma-ray detection complements information gained from measurements of cosmic-ray isotope and element composition. Isotopic abundances measured by the Cosmic Ray Isotope Spectrometer aboard the NASA Advanced Composition Explorer spacecraft are consistent with a cosmic-ray source comprising a mix of ~20% massive-star ejecta (stellar wind and core-collapse supernova ejecta) and ~80% normal interstellar material (ISM) with solar system abundances (*6*, *7*). Additionally, measurements of elemental abundances from C through Sr (*8*) show improved ordering by mass when compared to the same ~20 to 80% mix instead of that obtained when compared to only normal ISM abundances. These cosmic-ray measurements point to OB associations and their superbubbles as the likely source of the material and acceleration of a substantial fraction of cosmic rays.

Ground-based gamma-ray telescopes [VERITAS, HESS, and Milagro (*9*)] are also providing important observations of massive-star regions. Recent VERITAS results have revealed the detailed morphology and spectra in the Cygnus region, including spatially resolved TeV emission from γ Cygni and Cygnus OB1 (*10*).

Ackermann *et al*. have identified a particular superbubble as one specific source of cosmic rays, while direct observations of cosmic rays identify superbubbles as a class of astrophysical objects in which cosmic rays originate. To understand the processes occurring in OB associations and their superbubbles, it is useful to think about the time ordering of events in OB associations (see the figure). The lifetime of the association is divided into two epochs—the Wolf-Rayet (WR) epoch and the primary supernova epoch. The WR epoch is the time period dominated by the winds and ejecta of the most massive stars, with mass >40 $M_\odot$. It begins upon star formation within a giant molecular cloud and ends ~6 million years later. At the end of the WR phase, the massive stars core-collapse, and some undergo a supernova explosion, and some form black holes, depending upon their metallicity (*11*). The primary supernova epoch begins at that point and concludes when the least massive star that can core-collapse undergoes a supernova, ~40 million years after star formation. These supernova shocks expand as bubbles and coalesce, creating a superbubble. In the WR epoch, shocks formed by the high-velocity winds may accelerate cosmic rays; and in the primary supernova epoch, supernova shocks are likely the primary accelerators of material.

The ages of the Cygnus OB2 and NGC 6910 clusters studied by Fermi are quite young, ~4 to 6 (*12*) and 6 million years (*13*), respectively. Thus, their age puts them near the boundary of the two epochs. Either cluster may have already had several supernovae.

The Fermi observations reported by Ackermann *et al*., together with measurements of cosmic-ray elemental and isotopic composition, suggest that OB associations and their superbubbles are likely the source of a substantial fraction of galactic cosmic rays. Continued studies of these regions in gamma-ray emission and cosmic-ray abundance measurements offer rich potential for understanding the detailed nature of cosmic-ray origin.

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