On the Threshold of Cherenkov Astronomy

Radiation of extremely high energy from several celestial objects is leading astronomers to extend their science's spectral range yet again

By DIETRICK E. THOMSEN

How high in energy does the radiation from celestial objects go? Is there some upper limit?

Visible light — to which astronomy was confined for millennia — occupies a very short stretch of the spectrum of electromagnetic radiation. Only in the last four or five decades has astronomy been technically able to extend itself into either the longwave, low-energy radio range or the shortwave, high-energy range of X-rays and gamma rays.

As astronomers have pushed their techniques to higher and higher energies, they have discovered many interesting phenomena, some associated with objects already known and some related to objects found for the first time in the new energy range. Now, on the threshold of a range of very high-energy gamma rays that they call TeV or Cherenkov astronomy, they expect more new developments.

TeV is the abbreviation for tera-electron-volt — that is, 1 trillion (10^{12}) electron-volts — and the TeV astronomy range is counted somewhat arbitrarily from 10^{11} to 10^{14} electron-volts. A gamma ray of 1 TeV energy has a wavelength about a trillionth of a micron or 10^{-16} centimeter. (Visible light runs from about a third of a micron to almost 1 micron.) In the TeV range, the particulate nature of electromagnetic radiation is much more manifest than the wave nature, and scientists tend to talk of particles, that is, photons, rather than waves.

One TeV also happens to be the highest energy to which the accelerating machines of particle physicists — or one of them, the Tevatron at the Fermi National Accelerator Laboratory in Batavia, Ill. — can raise the energy of a proton. When accelerators of this energy were first planned, some physicists wondered whether anything in nature produces particles of such high energies. Astronomers have now found several objects that do, including the Crab nebula, the Crab pulsar, the Vela pulsar, Hercules X-1, Cygnus X-3, 4U0115+63, Centaurus X-3, PSR1953+29 and LMC X-4. All but PSR1953+29 are known X-ray sources. Most of them are pulsars, and one, LMC X-4, is outside our galaxy, in the Large Magellanic Cloud. According to Richard C. Lamb of Iowa State University in Ames, radiation into the peta-electron-volt or 1,000-TeV range has recently been detected from the Vela pulsar, LMC X-4 and Centaurus X-3.

The discovery of TeV gamma ray pulses from binary X-ray pulsars was quite unanticipated, according to Lamb and Trevor C. Weekes of the Harvard-Smithsonian Center for Astrophysics' southwestern station at Amado, Ariz. "Neither X-ray behavior, nor 100-million-electron-volt observations, nor theoretical models predicted this phenomenon. Thus TeV astronomy gives a fresh perspective on these intriguing objects," they wrote in a paper distributed in Ames at the recent meeting of the American Astronomical Society.

Theoretical consideration of how the binary X-ray pulsars emit TeV gamma rays is just beginning. At the Ames meeting, Peter W. Gorham of the University of Hawaii at Manoa described some of the observations of Hercules X-1 done at the Whipple Observatory and some theoretical conclusions he drew from them and expressed in his recent doctoral dissertation. Hercules X-1 is known as an eclipsing binary X-ray pulsar. Presumably it consists of a neutron star — the actual pulsar — orbiting around a more ordinary sort of star, known as HZ Herculis.

The TeV gamma rays from Hercules X-1 come episodically. There were seven such bursts during the 1984-85 period of the observations under consideration, and the bursts covered about 8 percent of the observing time. The gamma ray bursts seem to be associated with three periodicities that have been determined from the X-ray observations: an X-ray pulsar period of 1.7 seconds; a 1.7-day orbital period with a 6-hour eclipse; and a 35-day high, low and off modulation of the X-ray emissions.

The strongest gamma ray emissions come during the X-ray eclipses. Because the gamma ray emission persists after the beginning of the X-ray eclipse, Gorham concludes that the source of the X-rays and the source of the gamma rays are not geometrically coincident. Presumably the X-rays come from the neutron star and are cut off when the neutron star moves behind its companion, HZ Herculis. Gorham suggests that the gamma rays come from high in the atmosphere of HZ Herculis, from the limbs or edges of the star's disk as it would be viewed from earth.

He proposes that protons are accelerated to very high energies in the atmosphere of the neutron star. As they leave the neutron star, the magnetic field of HZ Herculis constrains them to move in curved paths, along which they strike the upper atmosphere of HZ Herculis. HZ Herculis needs only a very weak magnetic field — one-tenth of a gauss, or about a fifth of the earth's field — to accomplish this.

In the atmosphere of HZ Herculis, the protons strike neutrons, producing pions and the TeV gamma rays. The gamma rays come off in straight lines, and only those pointed directly at the earth will reach observers here. However, the paths of the protons that produce them vary in curvature according to the energy of the protons. Gamma rays of a range of energies — all pointed toward the earth — will be produced by protons of a range of energies that have come over paths of different curvatures from different points in the neutron star's orbit to reach the same location in the atmosphere of HZ Herculis. The protons of highest energies, which produce the highest-energy gamma rays, will follow the shallowest curvatures and so come from points where the neutron star is nearly or actually behind HZ Herculis as viewed from earth.

TeV astronomy is also known as Cherenkov astronomy because much of the detection of these high-energy gamma rays occurs through the medium of Cherenkov radiation, which is named for the discoverer of the effect, the Russian physicist Pavel Aleksandrovich Cherenkov. The effect occurs when charged particles moving through a transparent medium faster than the speed of light in that medium emit light. When the TeV photons strike the earth's upper atmosphere, they produce a shower of particles. Some of these particles move so fast that their velocity is greater than the velocity of light in air. Arrangements of photodetectors and photomultipliers on the ground detect the Cherenkov radiation from the particle showers triggered by the TeV gamma rays hitting the atmosphere.

The recent increase in the number of known sources of TeV gamma rays has encouraged plans for new and more sensitive detecting equipment for the Cherenkov light. Three such planned instruments were discussed at the Ames meeting. They belong to the "Whipple Observatory collaboration" (the Smithsonian Astrophysical Observatory, Iowa State University, the University of Hawaii and University College, Dublin), the group of institutions working on Mt. Haleakala on the Hawaiian island of Maui (the University of Wisconsin, Purdue University, the University of Hawaii and the University of Athens) and several institutions working at Sandia National Laboratories in Albuquerque, N.M. (the University of California at Riverside, the Jet Propulsion Laboratory, the University of Michigan at Ann Arbor and Sandia). Other institutions that have engaged in this kind of observation include the University of Durham, England, the Crimean Astrophysical Observatory on Mt. Semirodriki in the Soviet Union, the University of Tokyo, the Yerevan (Armenia) Physics Institute and the Fly's Eye telescope at Dugway Proving Ground, Utah.

Lamb and Weekes described the Whipple Observatory collaboration's plans for HERCULES (High-Energy Radiation Cameras Using Light-Emitting Showers). The present detector at the Whipple Observatory, which is located on Mt. Hopkins near Amado, Ariz., uses a 10-meter optical reflector to throw light on an array of 37 phototubes. The Cherenkov light from a shower comes in a conical pattern that makes either a circle or an oval on the ground. The array of phototubes determines the shape of this pattern according to which of the phototubes are triggered and what intensity they see. Analysis of the shape and intensity data gives such information as the direction of arrival of the triggering gamma ray and its energy.

HERCULES will use the same 10-meter reflector with an array of 193 phototubes. In addition, a second camera, modeled on the existing 39-phototube array, will be set up 120 meters away from the main camera. This should provide an even greater increase in sensitivity.

At the meeting, Lamb and Weekes distributed a graph comparing the expected capabilities of HERCULES with those of present detectors. Their graph indicates that HERCULES should be able to see sources around 10 times fainter than those now detectable over the energy range now available, and should extend the energy range slightly at both ends, to run from somewhat above 10^{10} electron-volts to about 10^{14} electron-volts. Weekes told SCIENCE NEWS they are asking for $1.5 million. If they get the money, he says, the instrument could be ready by 1989.

William Fry of the University of Wisconsin at Madison described a "new type of atmospheric Cherenkov radiation detector" to be built on Mt. Haleakala. Unlike HERCULES and existing detectors that consist of arrays of phototubes with overlapping fields of view, this detector would consist of two small telescopes with apertures of 10 or 20 centimeters set far apart so that their fields of view do not overlap. The "pancake" pattern of light cast on the ground by one of these showers is something like 60 meters across, Fry says. Coincident observations from the two widely separated telescopes can determine how high in the atmosphere the shower started, how wide its opening angle is and so forth. For energies above 10^{14} electron-volts, it should give a higher signal rate than any existing Cherenkov telescope, Fry claims. He estimates its cost at $250,000.

A stereoscopic detector is also planned at Sandia, according to O. Tumay Tumer of the University of California at Riverside. This will use two 11-meter reflectors casting light on arrays of seven 5-inch-diameter photomultiplier tubes. The two installations will be 41 meters apart. For better timing of showers, a third reflector, this one 7 meters across and reflecting light on a similar phototube array, will be placed 240 meters from the other two.

If the new equipment is built, the astronomers involved expect to detect tens of additional representatives of the three classes of TeV gamma ray sources they already know about: radio pulsars, X-ray binary pulsars and active galaxies. Of these they can ask questions such as: Where do cosmic rays originate? What kinds of objects govern the high-energy activities in our galaxy? And — the question that Gorham has already begun to address — how do X-ray binary pulsars emit bursts of TeV gamma rays?

Finally, they can expect the unexpected. Lamb and Weekes write: "The 'eyesight' of a frontier science to see where it is going is generally bad. Many times the biggest and most important developments are in totally unanticipated areas." □