301/754-7289

PROJECT DESCRIPTION

LIGO

- First Instrument to observe the universe by entirely new medium of gravitational radiation

- Two 4 km "L"-shaped vacuum systems, housing advanced laser detectors

RADIO TELESCOPE

- Fully steerable, 100-meter class aperture, high performance radio telescope, operable to 7mm or better

- Located in the National Radio Quiet Zone and designed to minimize interference from man made and natural radio signals.

SCIENTIFIC OPPORTUNITIES

LIGO

- New tool for fundamental physics and astronomy research

- First detection of gravitational radiation and exploration of its properties (velocity, polarization, etc.)

- Research is of a caliber that could lead to Nobel Prize

- Opening of a window to the universe which is radically different from electromagnetic, cosmic-ray, or neutrino astronomy

- Study of astronomical objects such as black holes, supernovae, pulsars, galactic nuclei, compact binaries, and the early universe

RADIO TELESCOPE

- Replace and upgrade capability for observations at radio wavelengths, with access to center of the Milky Way galaxy

- Studies of structure of the universe, gaseous content of galaxies, solar/stellar phenomena, molecular clouds and star formation, evolution of galaxies, and the solar system

- Applications to space- and ground-based very long baseline interferometry (VLBI)

COST CONSIDERATIONS

LIGO

- o Construction techniques and cost estimates studied for various sites since 1983
- o Construction $50M, of which $26M spent locally
- o Operations $2M/yr

RADIO TELESCOPE

- o Cost estimated with reasonable confidence at $75M, including design, contingency, and instrumentation
- o Construction contract $53M (included in $75M TEC) to outside vendor (TIW, RSI, etc.)

OVERALL PROJECT IMPLEMENTATION SCHEDULE

LIGO

- o 1989: $8.9M Engineering design, equipment, staff, site surveys
- o 1990: $10.9M Engineering design, equipment, staff
- o 1991: $30M Begin construction at East Coast site
- o 1992: $30M Continue construction at East Coast site, initiate West Coast site
- o 1993: $25M Complete construction at East Coast site, continue construction at West Coast site
- o 1994: $25M Complete construction at West Coast site, install receivers and begin operations at East Coast site
- o 1995: $10-20M Install receivers and begin operations at West Coast site

RADIO TELESCOPE

- o 1989: $4.0M Conceptual and engineering design
- o 1990: $1.7M Engineering design (continued)
- o 1991: $25.7M Fabrication and site development
- o 1992: $17.3M Erection of antenna structure
- o 1993: $17.3M Setting panels, outfitting, and testing
- o 1994: $9.0M Construction and operations

INTERNATIONAL IMPLICATIONS

LIGO

- Part of an international network involving the U.S.A, France, Italy, Great Britain, and West Germany
- Multinational agreement for complimentary investment in receivers and joint technology development

RADIO TELESCOPE

- Anticipated use as major ground station for space VLBI satellites Radioastron (USSR) and VSOP (Japan)
- Additional to world-wide network of ground-based VLBI stations, including antennas in Europe, Australia, and across the U.S.

CURRENT STATUS

LIGO

- NSB Project Development Plan approved 1984
- Endorsements: NSF Adv. Comm. for Physics (1983)
NAS Physics Survey (1986)
Int. Soc. for Gen. Relativity & Grav. (1986)
- 16 years of prototype R&D
- Conceptual design nearing completion

RADIO TELESCOPE

- Recommended by Radio Astronomy Panel of "Field Committee"
- U.S. user workshop (Greenbank, West Virginia 1988)
- Uses advanced technology for panels and support system and design for reducing aperature blockage
- Conceptual design recently initiated

EMPLOYMENT IMPACTS

LIGO

- Short term employment for 400 man-years during construction
- Long term operations staff of 20
- 5 FTE visiting scientists

RADIO TELESCOPE

- On-site construction crew brought in by contractor
- 140' to be mothballed within a few years
- 100-150 on-site users/year
- NRAO presence at Green Bank continues at present levels

LEGISLATIVE REQUIREMENTS

LIGO

- No specific authorization legislation required. NSF Organic Act and current five year authorization act provide sufficient authorization for project implementation, provided adequate resources are appropriated.

RADIO TELESCOPE

- No specific authorization legislation required. NSF Organic Act and current five year authorization act provide sufficient authorization for project implementation, provided adequate resources are appropriated.

DRAFT

March 1, 1989

LASER INTERFEROMETRIC GRAVITATIONAL OBSERVATORY (LIGO)

After much consideration of the various options, NSF has concluded that LIGO represents an important scientific opportunity that should go forward at this time. LIGO is a chance for the National Science Foundation to respond quickly to a unique scientific opportunity to support highly innovative and forefront research to push back the frontiers of knowledge.

PROJECT DESCRIPTION

LIGO will be a major scientific research facility whose purpose is to detect and measure gravitational waves. Gravitational waves are something scientists have wanted to observe since Einstein first predicted their existence, but only recently has the technology been developed to make this possible. The reason they are so difficult to detect is that the effect is very small; it is necessary to detect movements of less than the diameter of a single atom. Gravity waves will provide a fundamentally new way to view the universe. This development will be at least as revolutionary as radio and X-ray telescopes. LIGO will see further away, earlier in time, and penetrate deeper into space and astronomical systems than anything ever conceived before.

A LIGO site would consist of a control building with two large vacuum tunnels (above ground) at roughly right angles and 4 kilometers (2.5 miles) long. Two essentially identical LIGO sites are required "by the physics" of the observation. The sites must be separated by at least 1000 miles. LIGO's vacuum tunnels and control room would house some of the world's most technologically advanced lasers, mirrors, optics, and computers. The facility would operate over the long term, both as a basic research center for continually improving and developing technology, and also as an "observatory" to which visiting scientists from around the world would come to make observations.

CURRENT STATUS

LIGO has undergone 16 years of prototype development by scientists in the U.S. and Europe. Since FY 1985 NSF has provided about $12M to support LIGO prototype development and planning. Conceptual design is nearly complete. Construction techniques and cost estimates have been developed by Stone and Webster, A.D. Little, and JPL working with scientists at MIT and Caltech. A construction proposal will be submitted to NSF before the end of this summer.

LIGO has been thoroughly reviewed and prioritized by the U.S. and international scientific community. It has been endorsed by the

National Academy of Sciences in the "Brinkman" report and the NSF Physics Advisory Committee as the highest priority project in ground based gravitational research.

The National Science Board approved the project development plan in 1984 and has regularly received briefings on the project since that time--most recently in May 1988. These actions have prepared the National Science Board to review the forthcoming construction proposal.

The Office of Management and Budget has regularly supported the research and development budget requests for LIGO over the last several years and will be receptive to project construction and implementation.

As with other NSF projects, no specific authorization legislation is required. Section 3(a) of the The Foundation's organic act (42 U.S.C. Sec 1862) authorizes the Foundation:

> to initiate and support basic scientific research and programs to strengthen research potential...at all levels in the mathematical, physical...and other sciences...by making contracts or other arrangements (including grants, loans, and other forms of assistance) to support such scientific...activities.

The current five year authorization (P.L. 100-570) also provides sufficient authorization for project implementation, provided funds for the project are appropriated.

SCIENTIFIC OPPORTUNITIES

LIGO represents a new tool for fundamental physics and astronomy research, with capabilities far surpassing other current instruments. It will permit the first detection of gravitational radiation and exploration of its properties (velocity, polarization, etc.). The work that could be accomplished with LIGO is of a caliber that could likely lead to a Nobel Prize. Gravity wave observations would open a new window to the universe that is radically different from cosmic-ray, radio or optical astronomy. It could also dramatically enhance the study of astronomical objects such as black holes, supernovae, pulsars, galactic nuclei, and the early universe. LIGO will be both a long term observatory as well as a research and development facility.

INTERNATIONAL IMPLICATIONS

Strong groups of capable scientists already exist in Western Europe. A new group to pursue gravity wave detection has also been created in Japan. An international agreement has been reached to collaborate for maximum payoff for both physics and astronomy in the coming decades. The U.S. remains, however, the world leader in this area with the ideas and creativity; the highest quality of scientists; and progress toward implementing construction and operation of such a facility. Construction will enhance U.S. leadership.

COST ESTIMATES, SCHEDULE AND ECONOMIC IMPACTS

Construction techniques and cost estimates, at various levels of detail, have been examined at over 150 sites within the U.S. since 1983. Total cost of design and construction of the first LIGO site is estimated at appoximately $75M. The tentative schedule and initial cost estimates for LIGO are shown below:

FY 1989, $4.8M to (in addition to the $4M already in the current year's plan) for engineering design studies, site surveys, equipment, and staff.

FY 1990, $6.8M to (in addition to the $4.2M already included in the FY 1990 request) for engineering design studies, equipment, and staff.

FY 1991, $15-25M to begin first site construction of which $3-12M is estimated for earthwork. FY 1991 budget not yet formulated.

FY 1992, $15-25M to continue first site construction of which $3-12M is estimated for earthwork. ($5M to begin construction at second site)

FY 1993, $5M to complete first site construction and begin installation of receivers at first site. ($15-20M to continue construction at second site)

FY 1994, $5M to complete installation of receivers at first site and begin operation at approximately $2.1M per year. (complete construction at second site $10-20M)

FY 1995, ($10M to install receivers and begin operation at second site at approximately $2.4M per year.) Operational site at first site continues at $2M per year.

Permanent staffing of the first LIGO facility would require approximately 20 persons; 10 people in full time residence dedicated to operations (site manager, computer programmer, electronics technician, mechanical/vacuum technician, plant maintenance technician, and 5 operators) plus 10 local people working under contract to maintain mechanical equipment. Researchers from around the world will want to use this world class facility. Scientists and engineers from nearby universities would have the opportunity to conduct research using LIGO as well as develop high school and collegiate educational activities that include LIGO. Local university personnel could become involved in the ongoing instrumentation R&D activities.

NATIONAL SCIENCE FOUNDATION
WASHINGTON, D.C. 20550

February 28, 1989

OFFICE OF THE
ASSISTANT DIRECTOR
FOR MATHEMATICAL AND
PHYSICAL SCIENCES

MEMORANDUM FOR ERICH BLOCH

From: Richard Nicholson

Subj: Recommendation for Construction of LIGO

You asked for my recommendation as to the priority of LIGO versus replacement of the collapsed radio telescope at Green Bank.

There is no doubt that a strong scientific justification exists for each of these projects, and in an unconstrained system I could be enthusiastic about going ahead with both of them. However, in terms of priorities, I believe a significantly stronger case exists for LIGO, and therefore it has my unqualified recommendation for the highest priority.

Some of my reasons for this recommendation are contained in the remainder of this memorandum.

LIGO

Detecting gravitational radiation has been an important scientific goal since Einstein developed the General Theory of Relativity early in this century. Since the effect is very weak, detection was long assumed to be impossible. However, with advances in technology during the past 15 years, particularly in lasers and super-reflective mirrors, it now appears that gravitational radiation could be observed with LIGO.

To detect gradational radiation would open an entirely new window in physics and on the universe (because the origin of the phenomenon is physically different from electromagnetic radiation). Many think the discovery would be worthy of a Nobel prize. While today it cannot be called astronomy, if successful, LIGO probably would be the "telescope" of the next century.

NSF is the only agency that supports basic research in gravitational physics, and has been solely responsible for the R&D on the LIGO project for the past sixteen years. This research has been spectacularly innovative and successful, including the construction of a prototype (a 1/100-scale version of LIGO at Caltech). Over this time the project has been extensively reviewed and evaluated. This review has included numerous project peer reviews, as well as reviews by the National Science Board, the NSF Physics Advisory Committee, and the National Academy of Sciences (the 1986 Physics Survey known as the "Brinkman" Report). In each case the project has received an unqualified endorsement, and in the latter two cases it was rated top priority. It also has been endorsed by an International Workshop (1986) that involved physicists from a variety of subfields of physics, not just gravitational physics, and by the International Society for General Relativity (1986). A Project Development Plan was approved by the National Science Board in 1984, and the Conceptual design stage is nearing completion.

In short, LIGO is a thoroughly researched, reviewed, and widely endorsed project. It could open an entirely new window in science and thus it has the potential of producing many unexpected and profound discoveries. It represents the very essence of basic research and the mission of the NSF. In addition, because it involves extremely creative scientists with a track record of pushing measurement technology to its very limits, it seems very likely, even certain, that LIGO will produce many practical spin-offs.

Radio Telescope

Of course, we only began discussing this project following the collapse of the 300-foot telescope at Green Bank last Fall, and therefore it has nothing like the 16-year history of LIGO with which to compare. Nevertheless, it is clear that, both scientifically and technologically, LIGO is revolutionary where the replacement antenna is evolutionary.

The collapsed antenna had been a workhorse, especially useful in large surveys, and had over the years provided a great deal of useful scientific data. Nevertheless, in a priority sense, this antenna had recently been placed in category "C" by a distinguished committee (the "Langenberg" report) established by NSF to review and set priorities for facilities in radio astronomy.

In the short time following the collapse, a good scientific justification has been developed by the U.S. radio astronomy community for replacing the collapsed telescope with a 100-meter class, high performance radio telescope. The proposed telescope would have several new features, such as the ability to work at millimeter wavelengths and to observe the galactic center, making it to a certain extent a replacement in name only.

Despite the scientific justification and the added capability, I see several *relative* disadvantages in terms of putting this project at the highest priority. First, while millimeter work is a high priority, the location at Green Bank is less than ideal due to atmospheric conditions. Thus, the scientists estimate that at best there would only be about 60 days per year when the weather conditions would permit full use of the higher performance of the proposed telescope, raising questions of cost-effectiveness.

Another concern has to do with overall priorities for the whole field of astronomy, including optical astronomy. New radio astronomy facilities have occupied a high priority at NSF for the past twenty years, starting with construction of the VLA in the seventies, and continuing with the construction of the VLBA in the eighties. To now construct another radio facility in the nineties, would most likely preclude any significant project for optical astronomy, given any realistic budget projections. This would therefore amount to nearly 30 years of NSF focusing on radio astronomy to the likely detriment of optical astronomy. Thus, in the interest of a balanced national program, I believe NSF should await the next "decade survey" before starting a major construction project in radio astronomy.

BACKGROUND INFORMATION FOR SENATORS BYRD AND ROCKEFELLER
REGARDING THE LIGO PROJECT: GREENBANK

Scientifically, LIGO is an extremely prestigious and exciting project (of Nobel Prize caliber) that would ensure the LIGO sites with a prominent position on the World's scientific map.

Following the two year construction phase, LIGO will also be a major research and development effort that will continue for many years. There will never be a time when the sensitivity of the instrument is as good as one wants it. The ongoing research and development effort would be needed to continually improve LIGO's sensitivity. Thus the existing infrastructure of the radio astronomy observatory could form the foundation for a permanent state of the art electronics and laser facility.

Approximately $50-55M (up to around $25M locally) would be spent during a construction phase at Greenbank for 400 man years during the two year construction phase of the project.

In addition to operational costs spent at Greenbank for radio astronomy (approximately $3.3M in FY 1989), an additional $2.1M per year would be required for LIGO activities when operational (targeted for FY 1994) increasing annual operating support from $3.3M up to $5.1M.

Assuming FY 1989 staffing levels at the radio astronomy observatory, installation of LIGO at Greenbank could increase employment at Greenbank over current levels by about 10-12 positions (If one assumed 8.5 positions were supported by the 300 foot telescope, the requirement of approximately 20 for LIGO operations is projected).

Visiting scientists at the rate of at least 5 per year will be housed at each LIGO site. The number of visiting scientists per year could increase when gravity waves are observed; there will be instant, world-wide interest in the project.

LIGO is estimated to use 1MW of electricity annually at a cost of $350,000 per year.

LIGO will have the potential for important spin offs in the area of stable high power lasers, optical components, and precision measurement technology.

LIGO will enhance insights gathered by observations in space. By combining data from all available sources, correlations between signals will be far more valuable than the separate components in locating the positions of sources and unraveling the complexities in their behavior.

LIGO could help NASA since LIGO's development of stable lasers will be useful for developing high capability communications links to satellites.

ESTIMATED COSTS

Estimates

REPLACEMENT RADIO TELESCOPE: GREENBANK

Preliminary Design..0.5
Design Contract...2.7
Construction 53.7
Project Management, Instrumentation and Contingency..18.7
Total Estimated Cost..75.0

FY89 $4m
FY90 $2m
FY91 $25m
FY92 $20m
FY93 $15m
FY94 $10m

Annual Operating Cost Estimate........................ 0.3

Est Annual Operating Costs of Existing Radio Observatory
without replacement instrument..................... 3.0

Total Est Annual Operating Costs of Existing Radio Observatory with 300 ft replacement telescope............... 3.3

LIGO: GREENBANK

Design, Site Survey, Related Equipment...............19.8
Construction..50.0
Installation of Receivers.................................. 5.0
Total Estimated Cost..74.0

Annual Operating Cost Estimate........................ 2.1

Total Est Annual Operating Costs of Existing Radio Observatory with LIGO...................................... 5.1

March 1, 1989

Terry Sovain

Questions for National Science Foundation

Independent of construction funding for the Very Long Base Line Array, funding for the radio astronomy has declined. The 1989 budget for operations is slightly less than 1984. Inasmuch as some of the money goes to support VLBA operations, the decline in funding has had an even more adverse impact on the ability of the National Radio Astronomy Observatory to maintain operations, particularly in the face of inflation.

What were the staffing levels at Green Bank in FY 1984 (by function) and what are those staffing levels now?

Staffing Levels at Green Bank

	1984 (Dec)	1989 (Jan)
Telescope Operations	18	14
Machine Shop & Cryogenics	15	11
Electronics	23	20
Plant Maintenance	17	13
Scientific Services	12	9
Administrative Services	13	8
Fiscal Office	8	5
Research Staff	3	0
Mechanical Engineering	4	0
VLBA Construction	3	4
Total	116	84

How much does the FY 1990 budget include for radio astronomy? Of those amounts, how much is dedicated to operations, and construction?

The FY 1990 Request includes funding for two National Astronomy Centers having radio astronomy facilities:

		FY 1989 Current Plan	FY 1990 Request
National Astronomy and Ionosphere Center (NAIC)	Operations	$ 6.15M	$ 6.35M
National Radio Astronomy Observatory (NRAO)		$30.11M	$31.21M
	Operations	(18.3)	(19.0)
	VLBA Construction	(11.8)	(12.2)

Radio astronomy is supported on research grants as appropriate to the subject matter.

How many staff are associated with the operation of the 140-foot and the 300-foot telescopes (by function).

Green Bank Operations Staff Assignments by Telescope - 1989

300-Foot (reassigned to other duties at Green Bank following collapse)

Telescope Supervisor	1
Operators	4
Scientist	1
Computer Programmer	1.5
Mechanical	1
	8.5

140-Foot

Telescope Supervisor	1
Operators	5
Scientist	1
Computer Programmer	1.5
Mechanical	3
	11.5

U.S. Naval Observatory (USNO)	11

Common Green Bank Support*

Electronics	20
Machine Shop & Cryogenics	8
Plant Maintenance	13
Scientific Services	4
Administrative Services	8
	53
Total	84

* USNO funds support seven full-time equivalents in this category, four positions are VLBA construction, one is associated with the summer secondary science teacher's institute, and five are in the fiscal division.

What would be the staffing levels at Green Bank were the 140-foot telescope to be mothballed? (Please list the affected positions by function).

The 140-foot telescope is the only telescope NRAO operates at Green Bank for its user community. If the 140-foot were mothballed, the rationale for NRAO's operation of the site would cease to exist. The staffing levels in Green Bank would then be entirely dependent on the U.S. Naval Observatory. It is difficult to predict the final staffing level of a stand-alone USNO operation; a rough estimate would be 10 to 15 personnel employed by USNO for as long as they retained an interest.

What were NSF's long-range plans for radio astronomy at Green Bank prior to the collapse of the 300 foot telescope?

Prior to the collapse of the 300-foot telescope, it was NRAO's plan to operate the 300-foot and the 140-foot telescopes as long as long as the scientific priority of each telescope remained competitive with other needs in radio astronomy and in astronomy as a whole. A recent review conducted for NSF to identify priorities among all radio astronomy facilities supported placed the 140-foot telescope in a group highly recommended for continued funding under all but truly disastrous funding levels and the 300-foot telescope in a group highly recommended for continued funding, but less so than other radio facilities.

For a long time NRAO has been considering the scientific requirements for a new large-aperture, fully steerable modern telescope that would replace both of the old telescopes. However, the Observatory's first priority, established with a national consensus, has been the Millimeter Array for which they planned to seek NSF construction funds. Because the new Green Bank telescope has applications in areas of research supported by NASA and the USNO, it was hoped they also would contribute to its construction.

What are NSF's plans for radio astronomy at Green Bank if the telescope is not replaced (be specific)?

If the 300-foot telescope is not replaced, NRAO will continue to operate the 140-foot with reduced staff levels. However, the long-range future of the Green Bank site cannot be in radio astronomy without a new large aperture telescope to replace the collapsed 300-foot and the 140-foot telescopes. It will not be cost effective to continue operation of the rapidly aging 140-foot telescope indefinitely. Priority must be given to new areas, such as operation of the VLBA, causing severe budgetary pressures on the remaining program.

What space applications did the 300 foot telescope have for NASA programs?

The 300-foot telescope was to make observations that would have enhanced two NASA programs. A survey of pulsars was planned to support the Gamma Ray Observatory mission. A survey of atomic hydrogen emission in the Milky Way was planned that would be valuable for interpretation of data from the Extreme Ultraviolet Explorer, ROSAT, and other soft X-ray missions.

What potential does a replacement telescope have for NASA programs?

In addition to the programs listed for the 300-foot telescope, a replacement telescope would contribute to programs in space very long baseline interferometry, planetary radar, and radio wavelength studies of objects observed with the Hubble Space Telescope.

How many staff will be dedicated to the gravity wave detector, on site at Green Bank (by function)?

After the initial construction phase, there will be 10 people in full-time residence dedicated to operations (site manager, computer programmer, electronics technician, mechanical/vacuum technician, plant maintenence technician, and 5 operators) plus 10 local people working under contract on development and manufacture of major new scientific components.

In addition, there will probably be 5-6 visiting scientists in residence from the user groups collaborating on mounting independent simultaneous experiments.

How many staff will be dedicated to the gravity wave detector at other sites, and type of staff?

The operating staff will be the same size, but the local manufacturing support is not anticipated to be available at more remote sites.

What will be the operating budget of the gravity wave detector at Green Bank, and other sites?

	GREEN BANK	SECOND LIGO INSTALLATION
Operations (staff)	$800k	$800k
Power (1 MWatt)	350	750
Supplies and expenses	100	100
Laser upkeep	250	250
Vacuum system upkeep	250	250
Physical plant maintence	250	250
TOTALS	$2.0M/yr	$2.4M/yr

In addition, it is anticipated that there will be $5.6M spent on several university user groups to carry out the science. This will be used for staff costs, parts and materials for receiver development, data analysis, travel and living expenses at LIGO, etc.

What applications would the gravity wave detector have for the space program?

Both ground-based and space research aim to further our fundamental knowledge of the universe--its origin and structure, as well as the mechanisms underlying the many interesting astronomical objects which occupy it. In a general way, the new information gained from the LIGO will enhance the insights to be gathered by observations in space. By combining data from all available windows (optical, infra-red, radio, x-ray, neutrino, and gravity wave) correlations between signals will be far more valuable than the seperate components in locating the positions of sources and unraveling the complexities in their behavior.

In addition, the technology development for the LIGO will help NASA in its space mission. For example, the development of stable lasers will be useful for developing high capability communications links to satellites.

An even more closely related application is that LIGO will surely be a precursor for the Laser Gravity Observatory in Space (LAGOS) project which NASA has in a study phase for a possible mission in the next century. This will search for low frequency (below 1 Hz) signals which are impossible to see on the earth due to the masking effects of seismic noise. Such signals are created by particularly interesting sources, e.g. extremely massive black holes, which would otherwise be impossible to ever observe. The LAGOS mission would consist of a laser system bouncing between satellites. It is conceptually like a LIGO scaled up by a factor of a million in size, and suspended in space.

Clearly, the technology developed for ground-based operation of the LIGO will be critical to the design of the even more complex LAGOS project.

Congressional Research Service
The Library of Congress

Washington, D.C. 20540

Memorandum

February 17, 1989

TO : The Honorable Robert C. Byrd and John D. Rockefeller, IV
Attention: Carol Mitchell and Amy Berger

FROM : Richard Rowberg and James Mielke
Science Policy Research Division

SUBJECT : **The Green Bank Observatory Proposals**

On November 15, 1988, the 300 foot diameter radio telescope at Green Bank, West Virginia, collapsed and was totally destroyed. The telescope was part of the National Radio Astronomy Observatory, headquartered at Charlottesville, Virginia, which is funded by the National Science Foundation. The loss is a severe blow to the United States astronomy effort, and calls for its replacement have come from many of the Nation's astronomers. The NSF, however, appears reluctant to commit to a replacement. Instead, it has offered to build the eastern segment of the proposed laser interferometer gravitational observatory (LIGO) at Green Bank. The LIGO, which is designed to detect gravitational waves from stellar objects, is a joint experiment which would be run by California Institute of Technology and Massachusetts Institute of Technology. The NSF has committed to the project, but the funding request for FY1990 is only for continued R&D on the detector at the same level as FY1989. Currently, the eastern segment of the LIGO is scheduled to be built near Columbia, Maine.

The principal issue is whether the LIGO is an adequate substitute for a new 300 foot telescope in terms of benefits to the state of West Virginia and to the Nation's scientific enterprise. This paper first presents an analysis of five specific issues that address the scientific controversy and the benefits to West Virginia. Following that is a section which discusses the scientific background to the issue. This analysis is not intended to be an argument about building the LIGO, but rather a discussion of the merits of building it at Green Bank instead of replacing the 300 foot radio telescope. Indeed since the LIGO is likely to be built in any case, the principal scientific question centers on the consequences to radio astronomy of not replacing the 300 foot telescope.

ISSUES

There are a number of issues that address the question of the relative merits of building either of these instruments at Green Bank. Information to address these issues was obtained from conversations with scientists either participating in or familiar with radio astronomy and gravitational waves, and from the literature.

1. **Just before the collapse of the 300 foot telescope, the entire Green Bank facility employed about 80 people. What would the personnel situation of a LIGO be after it is constructed and operating? Would there be any significant difference between the two facilities in terms of the technical support infrastructure needed near the site?**

The LIGO would require few to operate. One estimate is that about 8 to 10 personnel would be needed for daily operations. Even this number may be high because it is very important that noise due to ground movement be kept at extremely low levels. (See Background Section on LIGO). The presence of a few people and associated equipment may create too much ground noise, and the entire operation may need to be operated remotely. The low ground noise requirement as well as limited research dollars also mean that the other radio telescopes at Green Bank, the 140 foot instrument and the 85 foot interferometer operated by the Navy, are likely to be shut down if the LIGO is built there. In addition, it is possible that services provided for local areas by Green Bank -- such as fire and ambulance service -- would have to be discontinued.

If the 300 foot telescope is not replaced, however, the number of personnel located at Green Bank is also likely to drop significantly. The 140 foot telescope, which, as noted in the background section below, is deteriorating, may be shifted to remote operation for the rest of its useful life. Many researchers believe that the Green Bank observatory would not survive with only the 140 foot telescope. There are two other radio telescopes comparable in size in the United States, and budget pressures may dictate closing the instrument in Green Bank. As its use as an astronomical observatory drops, so would the need for support staff for the entire Green Bank complex. A related concern is the potential breakup of the community operating the Green Bank facility. It is an innovative group, and much of the value of the 300 foot telescope came through the expertise of the scientific and technical support staff. Without a replacement, there would be a loss of a critical mass of trained people.

2. **The discovery of new astronomical objects such as the pulsar in the Crab nebula, brought much attention to Green Bank. Given the nature of the LIGO, would similar or greater scientific prestige accrue to West Virginia should the LIGO detect gravitational waves?**

The detection of gravitational waves by the LIGO would result in substantial scientific prestige for the research team and, at the time of discovery, probably for the site. Such a discovery likely will receive a Nobel Prize in Physics. The absence of any detection, however, would probably result in a series of scholarly papers discussing detection limits. These papers likely would be of only moderate interest to scientists unless they could be used to show that gravitational waves from a stellar event do not exist when such a wave was predicted by theory. The capability of verifying that waves do not exist, however, is far from assured since there is still uncertainty about the theoretical estimates of the strength and wavelength of expected gravitational waves. Such proof also would first require the discovery of these events by optical or radio telescopes.

A further consideration is how the "prestige" of an observation would be allocated. With two detectors apparently required at widely separated locations, (see Background Section) and the research teams located at still other centers -- Caltech and MIT -- it is not obvious that either location of the LIGO detectors would receive much attention in the event of a discovery.

A 100 meter radio telescope, however, is likely to result in many important if not fundamental scientific findings. The history of the 300 foot instrument and the scientific objectives of the proposed 100 meter replacement telescope (see Background Section) are such as to ensure the production of a consistent rate of findings about the structure, origin and dynamics of the universe. One researcher estimated about 100 noteworthy research papers per year could be produced by a new, 100 meter instrument. An important reason for this is the existence of the radio quiet zone which helps to meet the low noise requirements for making such observations. A 100 meter radio telescope located in such a zone would be unique among radio astronomy facilities.

As a result, a new, 100 meter telescope at Green Bank is likely to keep that location in the scientific forefront for several years, although spectacular discoveries, such as the pulsar found in the Crab nebula in 1968 by the Green Bank telescope may be much less likely. The LIGO, on the other hand, does offer the potential for a high consequence discovery that would rank as one of the most important in 20th Century physics. Such a discovery would be a single event, however, and the probability exists that nothing of major importance will take place.

3. What would be lost to astronomy if there is no replacement for the 300-foot telescope of any kind for the next 10 to 15 years? Can all or part of that loss be made up with existing facilities elsewhere?

Even before the loss of the 300 foot telescope, the radio astronomy community, as described in the background section below, put together several proposals for a new, fully tracking instrument in the 100 meter size range. With the loss of the Green Bank instrument, the community as a whole feels that a new, 100 meter, fully tracking instrument should have the highest priority for funding of new radio astronomy facilities. Many call the loss of the 300 foot telescope a severe blow for radio astronomy. The only comparable instrument is in West Germany and the low frequency radio interference near it is so great that West German astronomers have come to Green Bank.

There is a larger telescope than the 300 foot at Green Bank, the 210 meter (700 foot) instrument at Arecibo in Puerto Rico. That telescope, however, has no capability to move independently of the rotation of the earth since it was constructed by digging a shell in the ground. Even though it is more sensitive because of its larger collecting area, the Arecibo telescope covers a much smaller portion of the sky than was possible with the 300 foot telescope, and the latter could perform projects that were not possible at Arecibo. The proposed 100 meter replacement with full tracking capability would be able to cover an even bigger fraction of the sky, nearly three times as much as Arecibo. When the 300 foot telescope was in operation, radio astronomers used both depending on which was optimum for the particular project. They did not duplicate each other and the same would be true for the 100 meter replacement. Radio telescopes are not built to do the same thing so the 300 foot instrument was unique as would be the proposed 100 meter replacement.

A particularly important feature of the 300 foot telescope was its location in a radio quiet zone. Green Bank is the only observatory in a truly radio quiet area and there is unlikely to be another such zone. Pressure exists from radio and TV broadcast interests, and from mobile radio telephone interests to reduce or eliminate the Green Bank zone. Such pressure is likely to increase if the 300 foot telescope is not replaced in a timely manner.

There are some radio astronomers in the United States who feel that replacement of the Green Bank 300 foot telescope should not be the highest priority in this time of very limited funds for radio astronomy. Some believe an instrument capable of receiving very short wavelength signals -- the millimeter array -- should be built first while others would rather put the money into enhancing the very large baseline array (VLBA). It should be noted that many astronomers believe that a new 100 meter radio telescope, as part of the VLBA, would also enhance the latter's capability. In general, however, the Nation's radio astronomers desire a large replacement telescope. While some of the lost capability resulting from the 300 foot telescope's collapse could be made up by clever use of existing facilities, there is, nevertheless, a substantial void in radio astronomy without that telescope.

4. **The 300-foot telescope was used by a large number of scientists for a wide variety of astronomical research over the last 25 years. The replacement telescope promises even more opportunities for such users if built. How would the LIGO compare?**

The LIGO could be a facility which could be used by a number of researchers _if_ it is successful in detecting gravitational waves and _if_ detection leads to the ability to determine features of the stellar sources of those waves. Meeting these conditions is rather uncertain at this time. First of all, the frequency of stellar events which could produce gravitational waves of significant strength -- pulsars, galaxy or black hole formation, etc. -- be high enough to allow an observation rate sufficient to obtain useful data from these events to characterize them. While most astronomers believe that stellar events which would produce gravitational waves are quite common in the universe, there is much less certainty about how many, if any, of these events could be detected. If an LIGO could only detect events occurring in our galaxy, for example, the instrument would find little use since such events are quite rare. Currently some researchers believe that detection of any event is unlikely. It should be noted that attempts to detect gravitational waves have been going on for nearly 20 years -- using metal bar detector technology -- with no success to date. Such instruments inherently are not capable of reaching the sensitivity limits of a laser interferometer, however, which is the rationale for developing the LIGO.

If the LIGO is successful at detecting gravitational waves, there still remains much work before it could become a practical astronomical observatory. There has been considerable theoretical work in determining the wavelength and magnitude of waves coming from various sources, although uncertainty about these quantities still exists. Verification of these predictions, once waves are detected, and the subsequent calibration of the LIGO is likely to take several years. In order to verify the source of gravitational waves, parallel observations by optical or radio telescopes probably will be needed. While this could occur without rebuilding the 300 foot radio telescope, the existence of another instrument in that size range with full tracking capabilities could aid such confirming observations. Further, significant modifications to the initial LIGO configuration would be needed to expand the range of wavelengths of gravitational waves that could be measured, although such modifications would be straightforward.

As a result of the uncertainty of detection and the time required to develop gravitational wave astronomy if detection were successful, it may be several years, if not longer, before the LIGO could be considered a user facility in a manner similar to a new 100 meter radio telescope. In the meantime the latter would find considerable use, certainly as much as the former 300 foot telescope. That instrument was widely used by astronomers from all over the world. Over 1000 astronomers and graduate students from universities in the United States alone used the telescope over the last 25 years. And, in one recent case, it was being used by four astronomers from Brazil, three from Australia, and three from the United States as well as four graduate students.

5. Which instrument offers the greater potential for including West Virginia University in collaborative research?

Currently there is no direct collaboration between the radio telescope and the West Virginia University although there are proposals for the use of the complex as a teaching site for West Virginia University students. A number of students have worked with computer personnel at the Green Bank facility, and more computer linkages are being set up. Whether West Virginia University graduate students and faculty eventually become users of any radio telescope located at Green Bank depends on the establishment of a radio astronomy program at the University. Such an event is more likely than the introduction of a comparable program to make use of an LIGO operating at Green Bank. As described in issue four, there are formidable obstacles to making an LIGO a user facility similar to a radio telescope. The West Virginia University is not involved with the proposed gravitational wave experiment, and the uncertainty of developing the LIGO into an observatory for a variety of users makes it unlikely that the University would want to set up a gravity program any time soon.

It should also be noted that many school children from throughout the state of West Virginia have visited Green Bank. Further, during the last two summers, Green Bank ran teacher training institutes, and the facility has been a popular tourist attraction with approximately 20,000 visitors per year. Duplication of these activities with an LIGO is unlikely because of the need to restrict human traffic to reduce ground noise, and because an LIGO would not present the teaching opportunities that a radio telescope does. The LIGO is a frontier scientific experiment which, even if successful in detecting gravitational waves, would not yield the kind of information of significant use as a teaching tool in the near future.

SCIENTIFIC BACKGOUND

RADIO TELESCOPE PROPOSAL

1. Radio Astronomy Background

All stellar objects emit electromagnetic radiation. The visible portion of the electromagnetic spectrum (optical frequencies) has been observed since the dawn of the human species. The invention of the telescope in the early 17th century greatly expanded mankind's capabilities in optical astronomy. Advances in optical telescopes continued from the first small instruments to the large telescopes of today including the 200 inch telescope on Mt. Palomar and the multi-mirror telescope (equivalent to a 273 inch mirror) on Mt. Hopkins in Arizona. The next large optical telescope is the Hubble Space Telescope which is due to be launched in 1992 aboard the space shuttle. Its launch has been delayed several years due to the Challenger accident.

In 1931, a researcher at Bell Labs discovered that stellar objects also emit electromagnetic radiation in the radio frequency portion of the spectrum. This portion is so named because radio and television broadcasts occur at these frequencies. It was soon clear that information about stellar objects could be obtained with instruments that received these radio emissions just as using optical telescopes could obtain information by gathering visible radiation from these objects. Further, it was discovered that many stellar objects existed which gave off large quantities of radio emissions but little or no visible radiation. These discoveries gave rise to an entire, new branch of astronomy known as radio astronomy.

In the 1950s, radio astronomy came of age with the construction of the radio telescope at Jodrell Bank near Manchester, England. In the United States in 1956, the National Radio Astronomy Observatory (NRAO) was organized with support from the National Science Foundation. The organization is managed by a consortium of nine eastern universities. The NRAO picked the site of Green Bank, West Virginia as the location for its first radio telescope, and in 1962, a 300 foot diameter radio telescope was completed. This instrument was followed in 1965 by a 140 foot diameter telescope at the same site.

2. The Green Bank 300 foot Telescope

The 300 foot telescope was built quickly and inexpensively. As a result, it was only capable of changing its orientation in one direction, its elevation. Changing orientation in the other plane, the azimuth, was accomplished as the Earth rotated. This limitation did not preclude the 300 foot from being a very useful instrument. The telescope was designed to observe radio emissions at frequencies which include that characteristic of hydrogen, the most common element in the universe.[1] Measurement of the 21 cm hydrogen emission wavelength allows astronomers to map regions of space that cannot be seen by optical telescopes, and to study the dynamics of stellar objects.

The 300 foot telescope was very productive over its life. It was one of the most powerful radio telescopes in the world and was the largest in the United States capable of surveying most of the Northern sky. The telescope was used to make detailed surveys of stellar radio sources including galaxies outside our own, and objects such as pulsars and gravitational lenses. These surveys are currently the most complete and detailed available to astronomers, and form the basis of more intensive exploration by optical telescopes when possible and by radio telescope assemblies which have higher resolution than the 300 foot. The latter include the very large array (VLA) in New Mexico and the very large baseline interferometer (VLBA) which consists of telescopes throughout the world including the 140 foot telescope at Green Bank.

The most notable discovery of the 300 foot telescope was proof of the existence of a pulsar in the Crab nebula. This discovery proved that pulsars -- sources of intense, pulsating radiation -- result from the collapse of the core of a star after it has exploded to form a supernova. By measuring 21 cm radiation, the 300 foot telescope proved to be a very good instrument for determining the shape and size of our own galaxy. In the same way, the 300 foot was used extensively to determine the distribution, size and motion of other galaxies in the universe.

3. The Replacement Proposal

In December 1988, a group of 56 astronomers gathered at Green Bank to discuss the consequences of the collapse of the 300 foot telescope. The result of that meeting was the initial stage of a proposal to replace the destroyed instrument. The draft report[2] notes that prior to the collapse, several studies had been undertaken that pointed out the need for a "large, general purpose radio telescope" which could detect radiation down to one cm wavelength, and which would have a diameter of at least 330 feet (100 meters). This instrument was recommended as a supplement to the 300 foot at Green Bank. Other reports have indicated that radio astronomy in the United States is currently facing severe difficulties because of deferred maintenance on many

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[1] The wavelength of this emission is 21 centimeters (cm) and radio telescopes are characterized by the wavelengths they can receive. The lower wavelength limit is determined by the smoothness of the telescope's surface. Before its collapse, the 300 foot telescope could receive wavelengths down to 6 cm.

[2] Scientific Considerations for the Design of a Replacement for the 300-ft Radio Telescope, Draft Proceedings of a Green Bank Workshop, National Radio Astronomy Observatory, December 1988.

of its telescopes. For example, the 140 foot instrument at Green Bank has an obsolete equatorial mounting, and its surface is suffering excessive deformations because of age. Therefore, the loss of the 300 foot telescope exacerbates what many believe was an already serious problem in United States radio astronomy.

With this background, the committee at Green Bank proposed a telescope which would be significantly more capable than the one it would replace. The tentative design calls for a 100 meter telescope which is capable of measuring radio emissions at wavelengths as short as 1 to 2 cm. The proposed telescope would be fully tracking, that is be capable of moving both in altitude and in azimuth. The proposed telescope should also incorporate design features that would keep interference from man made radio frequency sources to a minimum. Because Green Bank is a National Radio Quiet Zone, location of the new instrument there would be a "distinct advantage" according to the proposal. No other sites were considered in the draft report. Indeed, one of the more serious limitations to radio astronomy is the existence of unwanted radio noise just as light pollution has severely limited the possible locations for new optical telescopes. As indicated in the draft report, the cost of this proposed radio telescope is estimated to be 50 to 70 million dollars, and it could be operating four years after the start of engineering design. There would be many scientific benefits of a 100 meter, 1 cm wavelength radio telescope. It would expand extensively on the capabilities of the former 300-foot telescope. The full tracking feature and high sensitivity would allow much greater coverage for surveying radio sources, expanding the search for new galaxies and pulsars. The extended tracking range of the proposed instrument could lead to the discovery of more pulsars as well as more detailed studies of the physics of pulsars. This information along with a better picture of the distribution of pulsars which would be possible with the proposed telescope, is quite important in understanding the evolution of stars and the universe.

With the proposed telescope, the acquisition of hydrogen emission data from stellar sources beyond our galaxy would be greatly enhanced. This information would increase our understanding of the large scale structure of the universe, the structure of and evolution of galaxies, and the structure of galaxies soon after their formation. The latter is possible because radio signals which can now be received from very distant galaxies were emitted several billion years ago when the universe was in its early stages of formation. The expanded range of wavelength detection would allow extended studies of extragalactic molecular composition which could also help achieve a better understanding of the evolution of galaxies.

The proposed instrument would also expand the mapping of radio sources which was a major responsibility of the former telescope. The increased sensitivity could yield the discovery of new stellar radio sources which, in turn, would provide additional targets for more detailed study by the VLA and VLBA. In addition, the proposed 100 meter telescope, if made part of the

VLBA, could greatly enhance its capability to study very weak stellar objects.[3] Also, the new instrument could be used to support space based radio telescopes and other space probes. Linking space telescopes to full tracking, ground based instruments greatly expands the sensitivity of the space system in much the same way the VLA and VLBA work on the ground. Other benefits of a new 100 meter telescope would be the possibility of more detailed study of molecular radio sources in our own solar system including those of comets that orbit the sun, of solar radio emissions to better understand the properties and behavior of the sun, and of our galaxy in terms of its structure and dynamics. These possibilities are brought about by the greater sensitivity the new instrument would have, its full tracking capabilities and extended wavelength sensitivity.

GRAVITATIONAL OBSERVATORY PROPOSAL

1. Gravitational Waves

Gravity is the force that acts between all objects with mass. The magnitude of the force between two objects depends on the size of the objects' mass, a gravitational constant first calculated by Newton, and is inversely proportional to the square of the distance between the two objects. Gravity is the force which holds us on the planet, holds the planets in orbit around the sun and acts between all stellar bodies. The General Theory of Relativity developed by Albert Einstein in 1916, predicted that the force of gravity could manifest itself in the form of radiation -- a gravitational wave -- if the mass of an object were to suddenly change either due to acceleration or to a loss of material such as would occur if it exploded. In this manner, gravitational waves would behave similar to more familiar electromagnetic waves.

Gravitational waves, however, are much weaker than electromagnetic waves. A gravitational wave emitted by an electron would be more than 40 orders of magnitude (powers of ten) weaker that an electromagnetic wave coming from the same electron. Another difference is that gravity does not act at a specific point like electromagnetic waves do. For example, if a gravitational wave were to act on a test object, it would also act on the observation instrument in exactly the same way, thus making it impossible to measure the reaction of the wave on the test object.

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[3] The VLBA, by electronically linking a number of widely separated radio telescopes, is able to simulate a single telescope with an aperature equivalent to that separation distance. These distances, in the case of the VLBA, can be several thousand kilometers giving the VLBA a much greater sensitivity than any single radio telescope could have.

2. Detection of Gravitational Waves

Because of their importance for further verification of the theory of relativity and the prospect they hold for further study of stellar objects and phenomena, detection of gravitational waves would be a significant scientific achievement. Thus far, such attempts have failed, although indirect observation has occurred. The two characteristics of gravitational waves, their weakness and the absence of action at a point, put severe constraints on any attempt to detect them.

It is not feasible to detect gravitational waves produced by objects in the laboratory. A 500 ton steel bar rotating at a speed which would cause the bar to tear apart would generate a signal about 20 orders of magnitude too weak to be detected by instruments that are currently being proposed for detection of such waves. Only stellar sources are likely to produce waves that could be detected. These include, among others, binary stars (a two star system in which the two stars rotate around each other), neutron stars (pulsars) which result during the collapse of a star, supernova, the formation of galaxies, and black hole formation. The key aspect is a massive change in or acceleration of gravitational mass.

Indeed, the first evidence of the existence of gravitational waves occurred in 1974 while observing a binary star system. Careful measurements of the change in rotation period of the pulsars about one another showed that the pulsars were losing energy and would eventually collide. The rate of energy loss corresponded quite closely to that expected if the mechanism for energy loss was emission of gravitational waves. While clear evidence, no direct detection of the wave was possible, however, at the time.

Even from such massive sources, the waves will be very weak. The energy from a gravitational wave from a binary pulsar, for example, would change the separation of two test masses by 10^{-21} meters per meter of initial separation. This distance is one millionth the diameter of a proton. Waves from other stellar sources are predicted to give equivalent displacements. The first attempts to measure such waves used single, massive metal bars. The bars were carefully designed to be responsive to a gravitational wave of a selected frequency. If a wave passed through the bar, it would vibrate due to the force of the wave. The vibration could be measured by very sensitive strain gauges surrounding the bar. By careful suspension and the shielding against other sources of vibration, extremely small strains were able to be detected. The detection limit, however, is still about 1000 times too small to detect gravitational waves, and no signals have been detected by this method. Even though more sensitive bars are possible, most researchers now feel that this path will not lead to detection.

A point about this experiment that holds for any kind of detection method is the need for a pair of detectors separated by a long distance, on the order of a few thousand miles. This separation is to ensure that any signal picked up is not due to local disturbances. Since gravitational waves from stellar objects would bathe the entire earth and not appear just at a point, detection would occur at both locations nearly simultaneously. A local disturbance or false electronic signal, however, is very unlikely to show up at both places at the same time.

Another potential detection instrument is a laser interferometer. The relative displacement of two masses due to a gravitational wave will show up as a change in the light pattern formed by the superposition of two laser beams, each reflecting off one of the masses separated in space. The shift in this pattern, called an interference pattern, due to a given change of separation between the masses, grows as the length of the initial separation distance increases. In addition, the sensitivity of the detector depends on the total length of the path travelled by the laser light. Since this length is adjustable by making the beam reflect back and forth many times between mirrors, a very long path can be built in a reasonably sized instrument.

The instrument proposed to detect gravitational waves is a laser interferometer called a laser interferometer gravitational observatory (LIGO). A proposal to build one has been made jointly by California Institute of Technology and the Massachusetts Institute of Technology; the National Science Foundation has tentatively committed to the project. The NSF has asked for level funding in the FY1990 budget request for continued R&D on the detector, but has not yet requested funding for construction of the LIGO. The proposed LIGO is a large scale version of an instrument currently operating at Caltech, and is expected to cost about 60 million dollars. The Caltech interferometer has the test masses separated by an optical path of 40 meters. While it is quite sensitive, it is unlikely to detect gravitational waves from any but the largest and closest stellar sources. For example, it is possible that the Caltech instrument could detect waves from stellar explosions that occur within our own galaxy. Such events are rather infrequent, however -- they may occur about once every 30 years or be as rare as every 500 years -- ruling out this instrument as a practical detector. The proposed LIGO will have the test masses separated by four kilometers, a factor of 100 greater than the Caltech instrument, which it is hoped would allow detection of waves coming from stellar events that are expected to occur several times a year.

One of the major problems in detecting gravitational waves is the presence of background noise. With signals as weak as these, even the presence of air molecules bouncing off the masses would cause displacements much bigger than that of a wave. Thus, the test masses must be housed in a nearly perfect vacuum, and the 4 km long chambers separating the masses will have to be evacuated. In addition, all other sources of noise -- such as very low amplitude, background ground vibrations (seismic) and thermal excitation of the test masses themselves -- must be reduced below the signal level expected for a wave. Careful design and suspension of the test masses can damp out these vibrations. Also, as stated, building two identical interferometers and separating them by a few thousand miles will virtually eliminate false measurements due to seismic noise which is very unlikely to affect the two stations at the same time. If construction funds for the LIGO are requested and if they are granted by the Congress, one of the pair of interferometers making up the LIGO would be located southern California. The other, currently, is slated to be located in Maine. This latter is the unit proposed for Green Bank.

3. Scientific Objective

The primary objective of the experiment, of course, is the first direct detection of gravitational waves. If such detection is associated with a visual observation, such as would occur if the gravitational waves came from a supernova, the speed of the gravitational waves could be measured by noting the relative time of arrival of the two events. The next piece of useful information to obtain would be the direction from which the wave came. In order to do that, three detectors would be needed. While a third detector is not part of the current proposal, two projects are currently being proposed in Europe that could provide that third leg.

Because the wavelength of these waves is characteristic of their source, however, observation of gravitational waves could lead to a new realm of astronomy, making an LIGO truly an astronomical observatory. Gravitational waves can pass through objects that do not permit electromagnetic radiation to escape. For example, gravitational radiation from inside a collapsing star could, in principle, be detected while light and radio waves from that region would be trapped by the surrounding matter. The formation of a black hole also could be observed in principal by monitoring the gravitational waves that are generated during its formation. Electromagnetic radiation, on the other hand, does not escape from a black hole so its direct observation by standard astronomical means is not possible. Therefore, if it turns out to be feasible to observe gravitational waves of varying frequencies and intensities in a reasonably routine manner, a powerful new astronomical tool will have been created.

The extreme weakness of these waves as well as certain characteristics of the LIGO, however, makes achievement of such "routine" observation far from certain. The optical path of the LIGO must bear some quantitative relationship to the wavelength of the wave to be observed. While an LIGO would be adjustable, the current range of wavelengths that it could operate at may be many orders of magnitude smaller than those generated by stellar events. It may be necessary to build several interferometers at one site to hope to capture any useful information. Indeed, the current proposal is being built to house several interferometers of different path lengths for just such a purpose, although the instrument will not have all of these installed at first.

The LIGO is a high risk experiment. If successful just in detecting gravitational waves, a major step in physics will have taken place. Doing so, however, will require a substantial advance in the limits of current technology. ■