VII. GRAVITATION RESEARCH[*]

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RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

The research in this group is in the field broadly labeled experimental relativity. Our objective is an experimental investigation of the gravitational interaction and the measurement of cosmological observables.

Specific Projects

1. Astronomy in the Region 1-0.1 mm

Our present knowledge concerning the sky in the region between 1 mm and 0.1 mm is still very limited. This region of the electromagnetic spectrum includes the cosmic isotropic background radiation, thermal radiation by interstellar dust, and most likely discrete sources that are not visible in other regions of the spectrum, in particular, distant sources that may give information concerning the early history of the universe.

Our major effort in this area for the last few years has been to obtain a set of measurements of the spectrum of the isotropic background radiation in the region 3-0.5 mm (3-20 cm^{-1}), using a liquid-helium-cooled balloon-borne radiometer. In a series of measurements from September 1969 to September 1971 (reported in Quarterly Progress Report No. 105, pp. 17-53) we established that the isotropic background radiation follows a Planck distribution appropriate to a blackbody at approximately 2.7°K in the 3-12 cm^{-1} region. The blackbody peak occurs at 6 cm^{-1}. In the region beyond 12 cm^{-1}, atmospheric radiation, primarily from ozone and water, dominates the spectrum even at 40 km altitude.

In an effort to measure the spectrum in the region above 12 cm^{-1} we made a flight in October 1972 at 44 km altitude with a new complement of filters. One of these filters extends the measurement of the isotropic radiation to 16 cm^{-1}. Two other filters were included to measure the column densities of ozone and water separately. The results of this flight are still being analyzed, but indications are that the isotropic spectrum is a Planck distribution up to 16 cm^{-1} and that it is indeed the atmosphere that produces an excess flux for frequencies greater than 16 cm^{-1}.

Further measurements of the spectrum from balloon platforms with present infrared technology do not appear to be promising unless we can achieve altitudes of 60 km

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or higher. These experiments seem to be good candidates for space-shuttle flights.

Our major new effort in far infrared astronomy is a balloon-borne experiment to measure the isotropy of the background radiation in the spectral region 3-10 cm^{-1} which includes almost all of the energy of the cosmic background radiation and a minimal amount of atmospheric radiation. In principle, with a balloon-borne differential radiometer using existing technology, it should be possible to measure .01% anisotropies of the background radiation in a balloon flight of 2 hours.

The symmetry properties of the expansion of the universe can be determined by measuring the moments of the intensity distribution of the background radiation. It is believed that there should be a first moment in the distribution caused by the Earth's motion relative to the average rest frame of the universe – the co-moving reference frame. This anisotropy can be characterized by a temperature that is dependent on the direction of observation

$$T(\beta, \theta) = \frac{T_o(1-\beta^2)^{1/2}}{1-\beta \cos \theta},$$

where $\beta = v/c$, v is the velocity of the Earth relative to the frame in which the radiation is isotropic and of temperature T_o, θ is the angle between the direction of observation and the velocity v.

The bandpass from 3-10 cm^{-1} includes almost all of the energy of a 2.7°K blackbody so that the intensity is given by the Stefan-Boltzmann law: $I(T) \propto T^4$.

The variation in intensity as a function of direction of observation is then of order

$$\frac{\Delta I}{I} \sim 4\beta \cos \theta.$$

The largest known contribution to β comes from the rotation of the galaxy, $\beta \sim 10^{-3}$, which gives a .04% anisotropy. The proper motion of our local group of galaxies is unknown, and may be measured in this experiment.

2. Far Infrared Detection

We are engaged in an experiment to detect far infrared radiation by parametric up-conversion in CdS pumped by the 5145 Å line of the argon ion laser (see Quarterly Progress Report No. 100, pp. 54-58).

We are also making a study of "hot" electron effects in InSb; specifically, the radiation by hot electrons and the modulation of the far infrared properties of InSb by varying the electron temperature.

3. Gravitational Antenna to Search for Gravitational Radiation from Collapsing Stars and Pulsars

The gravitational antenna is a set of virtually free masses mounted on low-frequency suspensions that are arranged to form a Michelson interferometer. Gravitational radiation modulates the separation of the masses. The separation is measured with a null servomechanism system that maintains the interferometer on a single fringe. A 10-m version of the antenna has a theoretical sensitivity of 10^{-21} strain per square root of detection bandwidth between 30 Hz and 10 kHz. The principal technological developments accompanying the construction of the antenna are the development of a high-power argon laser with an amplitude noise approaching the Poisson noise limit and the design and construction of horizontal suspensions with extremely low mode-mode coupling. Principal optical components of the antenna are multipass delay lines including two spherical mirrors, or a corner reflector with a spherical mirror.

4. Geomagnetic Pulses

An experiment is in progress to search for coincident geomagnetic field fluctuations over a 100-km baseline which have amplitudes of the order of 10^{-3} G and rise times less than 10^{-1} s. Events of this nature could be the cause of the signals that J. Weber, at the University of Maryland, attributes to gravitational radiation. The instrumentation is extremely simple. Two 1-m^2 induction coils, each with buffer storage, are used to record the amplitude and rise time of geomagnetic fluctuations that exceed the threshold amplitude of 10^{-4} G in 10^{-1} s or less.

R. Weiss

A. MEASUREMENT OF INTRINSIC LASER PHASE NOISE

Joint Services Electronics Programs (Contract DAAB07-71-C-0300)

D. K. Owens

We report a measurement of the phase fluctuations in the oscillation of a gas laser caused by spontaneous emission. The phase fluctuations in the signal resulting from the heterodyne of two independent modes in the laser were measured with the instrument shown in Fig. VII-1.

The gas laser is a He-Ne laser operating at 1.153 μm. The discharge tube is placed in an axial magnetic field and, because of the Zeeman effect in neon, the laser oscillates at two closely spaced frequencies with opposite circular polarizations.[1-4] An etalon and an iris in the laser cavity limit oscillation to only one longitudinal and one radial mode for each polarization. Furthermore, the etalon can be rotated to equalize the cavity losses for the two circular polarizations. One of the cavity mirrors is mounted on a piezoelectric transducer in order to adjust the cavity resonance so that both polarization modes oscillate with the same intensity. Under these conditions, and for a sufficiently strong magnetic field, the difference (beat) frequency between the two oscillating modes is linearly proportional to the axial magnetic field strength.

The laser is incorporated in a servo system that locks the beat signal 90° out of phase to an external oscillator by controlling the magnetic field on the discharge tube. The servo removes low-frequency, large-amplitude fluctuations in the beat frequency and permits convenient access through the servo error signal to the laser phase fluctuations.

The laser beam passes through a linear polarizer that converts the two circularly polarized waves into a linearly polarized wave that is amplitude-modulated at the beat frequency. The radiation is detected by a germanium avalanche photodiode cooled to

200°K. The photodiode output is amplified by a low-noise, broadband preamplifier, squared by a Schmitt trigger and then applied to a phase detector and a frequency discriminator. The output of the phase detector (point Ⓐ in Fig. VII-1) is proportional to the phase difference between the beat signal and the local oscillator. The phase detector output is the servo error signal that controls the current in the solenoid coil around the discharge tube. The frequency discriminator facilitates the phase lock and ceases to be part of the servo system when the phase lock has been attained.

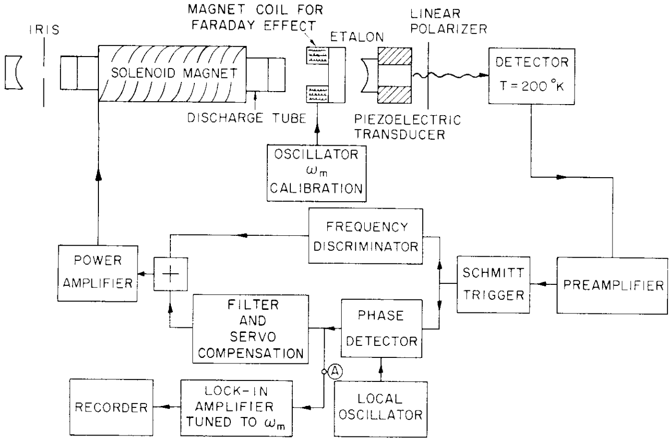

Fig. VII-1.

Servo system and He-Ne laser. The length of the laser cavity is 107 cm, and the discharge is 58 cm long. The mirrors have a 120-cm radius of curvature.

The power spectrum of the voltage fluctuations measured at Ⓐ is obtained by using a lock-in amplifier as a narrow bandpass filter. From these measurements it is possible to infer the spectrum of the laser phase fluctuations that would be present if the servo were not used. To do so it is only necessary to note that with respect to phase fluctuations, the servo system is linear and hence can be analyzed in the frequency domain. Then, at any specific frequency in the closed-loop configuration, the amplitude of the voltage at Ⓐ is proportional to the amplitude of the open-loop laser phase fluctuation. The constant of proportionality is frequency-dependent and is obtained by applying a sinusoidally varying magnetic field to the etalon. Because of the Faraday effect in the etalon glass, the magnetic field produces a time-variant difference in the refractive index for left and right circularly polarized light. In effect, the cold cavity optical path lengths for the two polarizations are differentially modulated so that the beat frequency becomes modulated at the frequency of the time-variant field. At Ⓐ this appears as a signal at the modulation frequency. The constant of proportionality is the ratio of the amplitude of this signal to the amplitude of the open-loop modulation of the beat frequency. The open-loop beat-frequency modulation can be measured by varying the magnetic field on the etalon at a frequency outside the bandwidth of the servo. The signal at Ⓐ is then independent of the servo and depends only on the gain of the phase detector and strength of the magnetic field on the etalon. These quantities can be measured and the ratio of the change in beat frequency to magnetic field strength calculated. This ratio is frequency-independent and serves to calibrate the instrument at all modulation frequencies. With this information, we can also determine the Verdet constant of the etalon glass.

Figure VII-2 shows the power spectrum[5] of the frequency fluctuations in the beat signal for output mirror transmittances of 4.3% and 1.6%. In all of these experiments the beat frequency was 150 kHz, the discharge current was 20 mA, and the laser output power was kept constant at 6.4 ± .3 μW per polarization by adjusting the etalon and cavity mirrors.

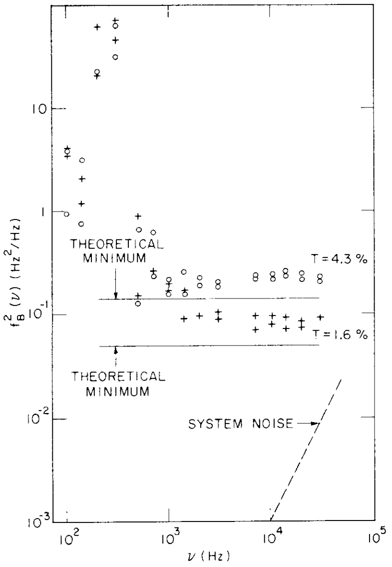

Fig. VII-2.

Power spectra of the laser frequency fluctuations for S = 1.65×10^7 photons per mode (1.6% case) and S = 6.2×10^6 photons per mode (4.3% case). The theoretical minimum of the power spectrum (determined from Eq. 1) is indicated for each case. System noise, which is primarily amplitude noise converted into phase noise in the Schmitt trigger, is determined by measuring the noise at the mixer output when the photodiode is illuminated by infrared radiation from an LED amplitude-modulated at the beat frequency. The photo signals from the LED and laser are equal.

The cavity Q for each case was measured by using an auxiliary 1.153 μm He-Ne laser to determine the linewidth of the Fabry-Perot resonances of the laser cavity. The Q was measured as $(9.9 \pm 1) \times 10^7$ for the 1.6% transmittance case, and $(9.7 \pm 1) \times 10^7$ for the 4.3% transmittance case. Since the power, Q, and discharge conditions are essentially the same for both cases, the only difference is in the radiation density stored in the laser cavity.

Above 1 kHz, the spectrum appears flat and clearly shows that the frequency fluctuations increase with decreasing radiation density in the cavity. For the 1.6% transmittance case, the number of stored photons per mode is 1.65×10^7 and the power spectrum is $f^2(\nu) = (9.6 \pm 2) \times 10^{-2}$ Hz^2/Hz; for the 4.3% transmittance case the number of stored photons per mode is 6.2×10^6 and $f^2(\nu) = (2.7 \pm .3) \times 10^{-1}$ Hz^2/Hz. Below 1 kHz, the spectrum is dominated by extrinsic sources such as acoustic and ground vibrations. The data strongly suggest that the frequency fluctuations above 1 kHz are due to spontaneous emission.

The spectrum of the intrinsic frequency fluctuations of a single-mode laser is given by

$$f^2(\nu) = \frac{D}{\pi}, \tag{1}$$

where D is the intrinsic laser linewidth.[6,7] A lower limit can be placed on D by using the formula derived by Scully and Lamb[8]

$$D = \frac{1}{2}\,\frac{\nu}{SQ},$$

where ν is the laser oscillation frequency, S the number of photons stored in the mode, and Q the quality factor of the laser cavity. The spectrum of the beat-frequency fluctuations is twice that of (1), provided that the two modes are independent. With previously given values of S and Q, we calculate the power spectra to be

$$T = 4.3\% \qquad f_B^2(\nu) = 1.4 \times 10^{-1}\ \mathrm{Hz}^2/\mathrm{Hz}$$

$$T = 1.6\% \qquad f_B^2(\nu) = 5.1 \times 10^{-2}\ \mathrm{Hz}^2/\mathrm{Hz}.$$

The measurements are consistent with theoretically predicted values.

It is possible to measure extremely small Verdet constants with modest fields by using the technique described in this report. For example, the etalon glass was found to have a Verdet constant of $|2.5 \times 10^{-3}|$ min/G-cm, where a field of 1.7 G gave a large signal-to-noise ratio. The intrinsic laser phase fluctuations limit our ability to measure differences of refractive index in transparent materials for right and left circularly polarized light of

$$n_R - n_L \geqslant \frac{f_B(\nu)}{f\tau^{1/2}}\,\frac{L_{\mathrm{laser}}}{L_{\mathrm{sample}}},$$

where τ is the integration time.

This technique may find application in the measurement of electron densities in tenuous plasmas, and holds some promise for making a measurement of the refractive index of strong electric or magnetic fields as predicted by quantum electrodynamics.[9,10]

References and Footnotes

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