SAMPLE

Great Observatories: LIGO

Hearing Gravitational Waves

Aira Astralis

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Conclusion

This free sample contains the Introduction and Chapter 1. The complete book contains the full contents above.

Introduction

The Laser Interferometer Gravitational-Wave Observatory is the strangest instrument in this series' shelf of instruments, and this volume is its biography. The great observatories of the previous books collected light: the telescopes of the classical era, the space telescopes of the century's end, the radio dishes of the modern age, every one of them a device for catching photons and reading the sky's brightness. LIGO collects something else. It listens. The observatory's twin stations, one in the desert of Washington State and one in the pines of Louisiana, each hold a pair of four-kilometer vacuum tubes laid out in an L, and inside each L a laser runs out and back a hundred times, its light folded between hanging mirrors, so that the machine can feel the fabric of space itself shiver by a fraction of an atom's width.

When a gravitational wave passes, it stretches one arm and squeezes the other, and the laser's interference pattern changes, and the machine writes down, in a stream of numbers, the passage of a disturbance that has crossed a billion light-years. The observatory is a microphone pointed at the universe.

The subject of this volume is therefore not an object in the sky but an instrument on the ground, and the series' method suits it, because the instrument's story is a complete history of an idea: a prediction made by Einstein a century ago and called by him too faint ever to detect; a search conducted for decades by a stubborn few with resonant bars that rang like tuning forks and heard nothing; a proposal mocked in committee and funded anyway, the largest and longest gamble the National Science Foundation ever took on a single project; and, in September of twenty fifteen, a signal in the first days of the upgraded machine's first run, a chirp rising through the audio band in a fifth of a second, two black holes a billion light-years away falling into each other and announcing it by shaking the space of Louisiana and Washington by one part in a thousand trillion trillion.

What follows is the full arc of the story: the physics of the waves, the engineering of the interferometers, the noise that had to be defeated, the detections that rewarded the patience, and the new astronomy that the chirps have opened. Anyone who reaches the last page will understand the machine's working and its worth, and will hold the series' one case study in hearing the sky.

A scope note completes the introduction: the volume's subject is the observatory, the machine and its detections, with the wider science of gravitational waves given only its supporting role. The bar detectors, the pulsar timing arrays, and the space interferometer missions appear as context

and future, their own stories belonging to other volumes; the theory's mathematical machinery is summarized where needed and not derived; and the detections' astrophysical consequences, the black hole demography and the neutron star aftermath, are covered as the machine's products rather than as the field's whole story, the observatory being the subject and the sky being its customer, the introduction's honest boundary being the machine's own fence line, four kilometers on a side, two stations, and everything they hear.

Chapter 1: The Discovery of LIGO

The discovery of LIGO is a discovery in two acts, and the first act belongs to Einstein. In nineteen sixteen, in the middle of the general theory of relativity's first years, he computed what his field equations allowed: a mass in motion should radiate ripples in the geometry of spacetime, waves carrying energy away at the speed of light, the fabric of space itself ringing like a struck surface. The prediction was radical and, Einstein thought, unusable; the waves any real motion could make were so faint that he doubted they could ever be measured, and for decades the papers debated even whether the waves were real or a coordinate artifact, the theory's own inventor at one point convinced the ripples carried no energy at all.

The idea survived its birth trouble: the mathematical community settled the reality question in the late fifties and early sixties, a conference in North Carolina and a paper by Bondi showing that the waves carry genuine energy, and the prediction stood as one of general relativity's last unverified consequences, a check the theory awaited for another half century.

The first attempt to cash the check was Joseph Weber's, and its failure is the founding lesson of the field. In the sixties Weber built resonant bars, great cylinders of aluminum suspended in vacuum and instrumented with piezoelectric sensors, tuned to ring if a gravitational wave of the right frequency crossed them; he claimed coincident events between separated bars in the late sixties, the physics community's attention was seized, and the claim collapsed, his reported event rate too high to be real, other laboratories building bars and hearing nothing, the field's first decade ending in a healthy skepticism: the waves were predicted, the bars were listening, and the bars heard nothing above the noise. Weber's failure was not useless; it founded the experimental community, taught the standards of coincidence and significance the whole field still uses, and posed the question the rest of the century answered: if the bars could not hear the waves, what could?

The answer, interferometry, was proposed independently on both sides of the Atlantic, and its American author is LIGO's founding figure. In the late sixties and early seventies, Rainer Weiss, at the Massachusetts Institute of Technology, was given the general relativity course no one else wanted to teach and worked out, in the course of preparing a laboratory demonstration, the design that would occupy his next forty-five years: a Michelson interferometer with kilometers of arm length, laser light bounced between suspended mirrors, a passing gravitational wave changing the arms' relative lengths and the interference pattern at the output, the sensitivity climbing with the arm's length and the mirror's stillness. His nineteen seventy-two

report, written for the students' benefit, remains the clearest document in the field, the design the modern machines still follow; Weiss taught a generation the trick of measuring changes a thousand times smaller than any prior instrument had held, and he kept the project alive through the decades when the National Science Foundation's patience was the field's only fuel.

The idea's other parent in Europe was Ronald Drever, the Scottish experimentalist who had built small interferometers in Glasgow, and the theoretical advocate who gave the physics community its confidence was Kip Thorne of Caltech, the relativity theorist who argued the field's case in committees and recruited Drever to the American project. The two laboratories, MIT and Caltech, joined under a single project in the early eighties; the design studies ground through the decade; the National Science Foundation took the unprecedented step of funding, in nineteen ninety-two and ninety-four, the construction of two large facilities at once, the Hanford site in Washington and the Livingston site in Louisiana, two stations because a real signal must appear in both, the coincidence being the whole defense against the local shakes and glitches that fool a single instrument.

Barry Barish, brought in to lead the project in nineteen ninety-four, reorganized it into the manageable program it remains, and construction began: the arms poured and pumped, the beam tubes evacuated to a trillionth of an atmosphere, the mirrors hung on silica fibers, the lasers locked.

The construction completed, the initial LIGO observing era opened in two thousand two and heard nothing, exactly as designed: the machine worked, its noise floor was honest, and the waves it could hear were rare or absent, the first run's silence being the field's most expensive null result. The upgrade, Advanced LIGO, rebuilt the guts of the interferometers between twenty ten and twenty fifteen: heavier mirrors, better suspensions, squeezed light in the works, the sensitivity goal a tenfold gain in distance and a thousandfold gain in volume, the machine built to hear mergers out to the billion-light-year range.

On the fourteenth of September, twenty fifteen, before the upgraded machine had formally begun its first observing run, both stations recorded the same fifth-of-a-second chirp, the signal matching the computed waveform of two black holes coalescing, and the century-long discovery closed its loop: Einstein's prediction detected, Weber's question answered by the machine his failure inspired, the two-act discovery complete, the observatory discovering, on its first working morning, the thing it was built for.

The discovery narrative's European thread deserves its own closing note, because the machine's design is partly a continental story. Ronald Drever's Glasgow interferometers and the German groups' Garching prototypes proved

the key techniques in the small machines of the late seventies and eighties, the mirror-stabilization tricks and the recycling ideas that the large design absorbed; the eventual European project, Virgo, grew from the same roots and joined the American machine as a partner rather than a rival, the field having chosen, early, the network model over the national one, the discovery's history being the story of two communities that decided to build one instrument in three countries, the observatory's biography being from the start a biography of cooperation.

The discovery history's funding narrative deserves its own full entry, because the machine's existence is partly a bureaucratic story, and the field tells it candidly. The nineteen eighty-three review of the Large Scale Projects, the committee that nearly ended the interferometer idea, produced the famous negative report, the panel judging the machine too expensive for its prospects, the project surviving the verdict by the founders' stubbornness and the foundation's divided internal counsel; the nineteen eighty-nine approval of the two-site construction, the decision the field regards as the courage point, the NSF's leadership betting the physics budget's credibility on an unproven instrument's two-decade silence; and the construction era's overruns and reorganizations, the mid-nineties' management crisis that brought the project's rescue by the reorganization Barry Barish led, the machine's biography including a near-death experience and a rescue, the discovery chapter's honest lesson being that the science's century was made possible by administrators' names the public never learned, the observatory's first discovery being also the discovery that patience can be funded.

The discovery history's technological prehistory completes the arc, the machine's own ancestry in the precision trades. The Michelson interferometer of the eighteen eighties, the light-optics experiment that failed to find the ether, gave the machine its geometry a century before the machine existed; the laser's invention in the nineteen sixties gave it its ruler; the vibration-isolation and the vacuum engineering of the mid-century gave it its quietness; and the digital computing of the century's end gave it its analysis, the observatory being a museum of the century's trades assembled into one instrument, the discovery chapter's closing genealogy being honest: LIGO was invented four times, once by Einstein as a prediction, once by Weber as an ambition, once by Weiss as a design, and once by the collaboration as a machine, the four inventions being the four generations the project needed, the observatory's biography being the twentieth century's precision history told as a single story.

One more discovery-history entry belongs to the machine's naming and the public's learning of it, the acronym's own life. The observatory's name is a

mouthful, and the culture shortened it instantly, the field being LIGO to the papers and the public alike, the acronym's uppercase having become the science's brand; the name's honesty being the machine's whole description in four words, the laser interferometer saying the method and the gravitational-wave saying the quarry and the observatory saying the ambition, the rare acronym that tells the truth; and the name's plural being the field's quiet correction, the observatory being two stations, the grammar of the detections' announcements always carrying the pair, the entry closing the chapter's history with the machine's own label held up to the light, the name being the last piece of the discovery the founders got exactly right, the project having been named for what it is and having become what it was named.

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ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.