Canadian Hydrogen Mapping Experiment (CHIME)

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Abstract:

CHIME is a revolutionary new radio telescope used for Cosmology, Fast Radio Bursts (FRB) and Pulsar Astronomy. Here, we focus on the FRB/Pulsar side of the telescope, we will explain how the telescope works and why it's unique design is revolutionary towards this field of astronomy.

Fig. 1: Telescope's half-cylinders with people for scale. [McGill Reporter]

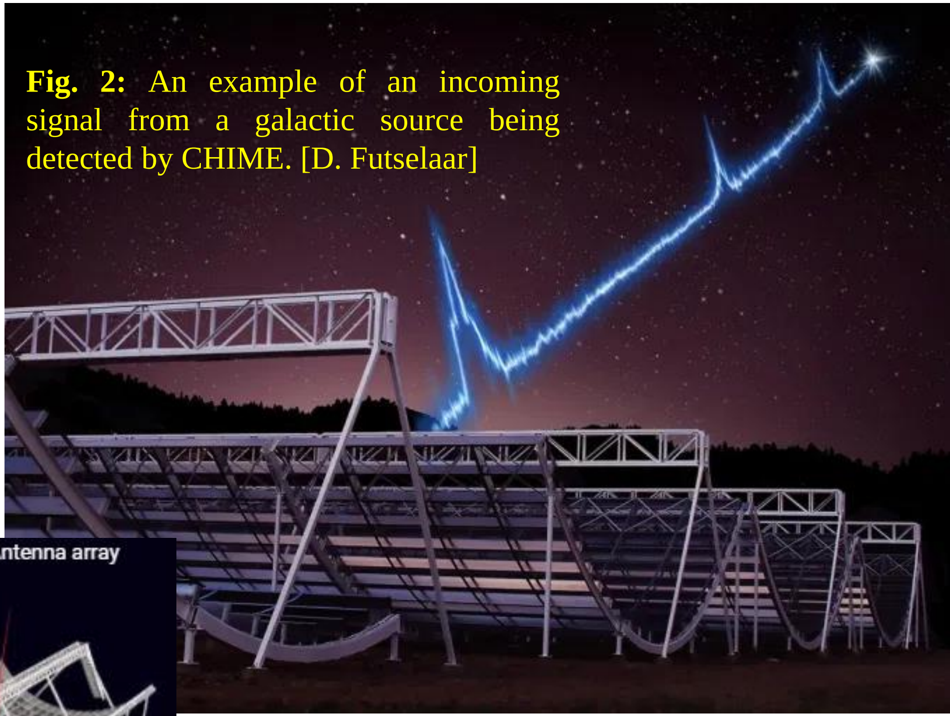

Fig. 2: An example of an incoming signal from a galactic source being detected by CHIME. [D. Futselaar]

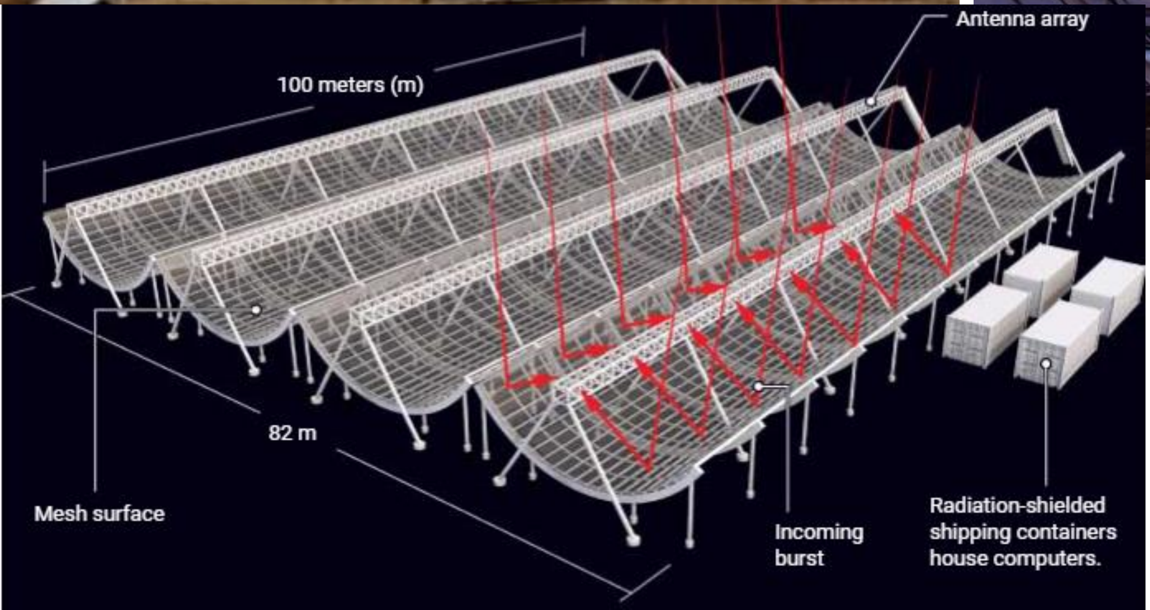

Fig. 3: Diagram showing how CHIME receives and reflect signals into the antennas. [C. Bickel/Science]

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Introduction/ Motivation:

- CHIME is a new project that started taking data in 2018. It's design is unique as it is a drift-scan telescope and therefore is not physically steerable.
- However, because of it's design it covers a much larger area of the sky, and because of clever optical and signal engineering, they are able to look at multiple locations in the sky at once.
- This means that the observation rate is much greater than previously used telescopes. As an example, the Arecibo Telescope and Greenbank Telescope are able to observe a pulsar once every 3-4 weeks, CHIME is able to observe once per day!
- These results will lead to much higher precision in the data and will help scientists such as NANOGrav make the first discovery of gravitational waves.

Radio-Astronomy Basics:

- A pulsar is a rapidly spinning neutron star that is the remnants of a massive star that has gone supernova.
- FRB sources are unknown! They probably come from magnetars, which are similar to pulsars, with much bigger magnetic fields.
- Pulsars are "cosmic clocks" since they spin so accurately that their signal is more reliable than atomic clocks. Their pulse period is extremely stable which makes them useful for experiments.
- One big current projects uses pulsars to try and detect gravitational waves. Small irregularities in the pulses over a long time is an indication of gravitational waves given off by a galaxy mergers in the universe.
- Currently NANOGrav is the group leading the effort using data from Arecibo and Green Bank.

Fig. 4: Full CHIME telescope with size labeled. [CHIME]

Fig. 5: 305 m Arecibo Radio Telescope before its recent collapse (12/2020). [Arecibo Observatory]

Fig. 6: Green Bank Telescope, world's largest fully steerable radio telescope.[NRAO/AUI/NSF]

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Apparatus:

- Four 20 m x100 m half cylinders direct incoming radio waves into an array of cloverleaf antennas. f/0.25
- Dual-Polarized, meaning that N-S and E-W waves can be detected.

Procedure:

- Signals are amplified and brought to a single digital correlator.
- Waves combine to create a "beam" that looks at a particular point in the sky.
- Data is sent to a science project or archiver.

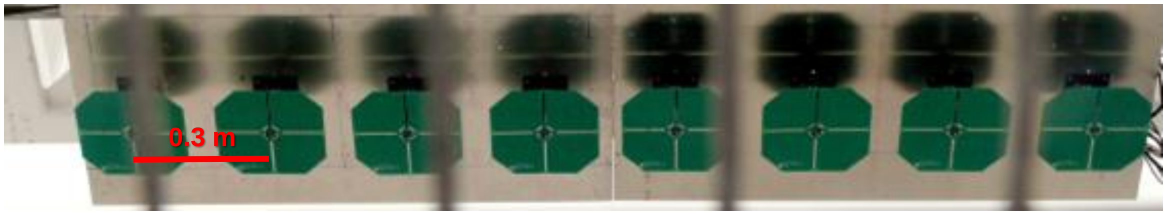
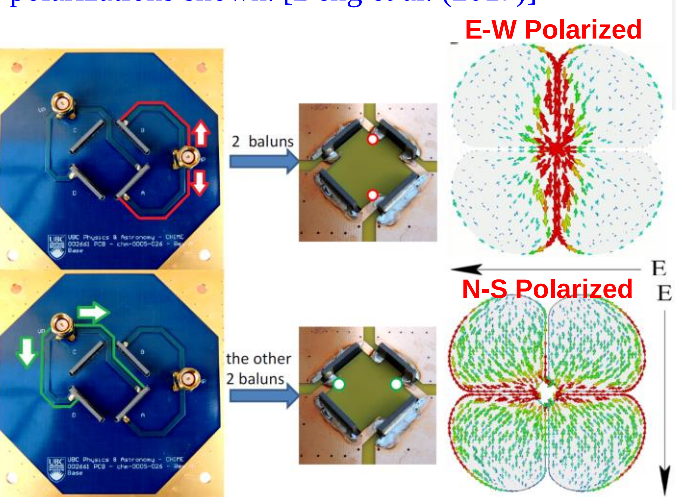
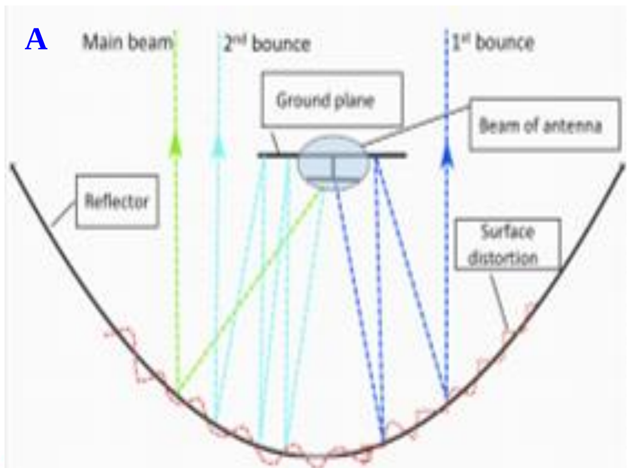
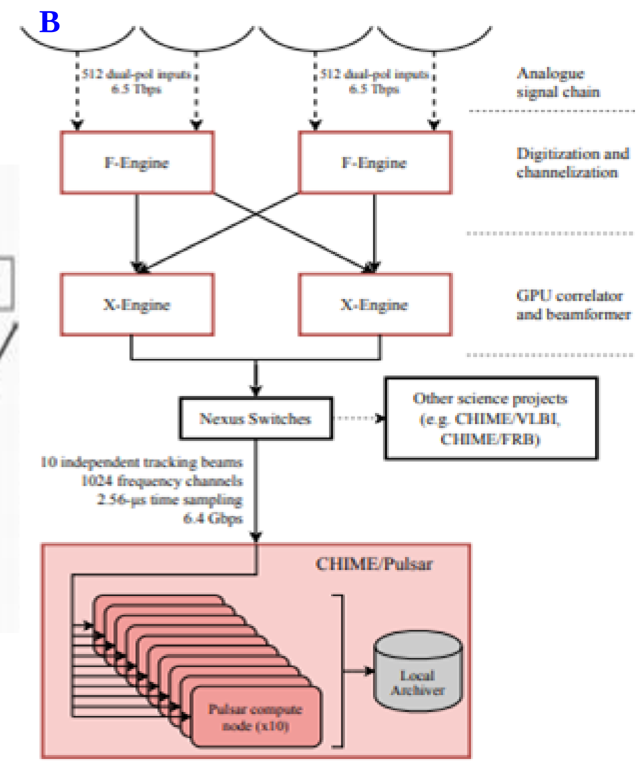


Fig. 7: Linear array of eight cloverleaf antennas installed at the focal line. Note the four slots cut to remove dielectric material from the gaps between the petals. [Deng et al. (2017)]

Fig. 8: (L) Arrangement of the antenna showing and how the capture of both polarizations. **(R)** Simulated currents for linear polarization at 600 MHz. E-W and N-S polarizations shown. [Deng et al. (2017)]







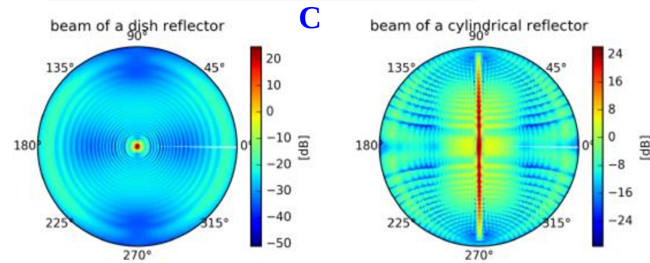


Fig. 9: A diagram of the simulated beam, showing how the waves are combined to create the observing beam. [Deng (2012)]
B Schematic of the CHIME signal path. Note Beamformer step where the beam is created digitally. [Amiri et al. (2020)]
C Shows the difference between a circular beam from a dish reflector vs. CHIME's fan-shaped beam. [Deng (2012)]

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Results & Discussions:

Over 700 FRBs Detected! These measurements give us information about dispersion measure (a measure of the matter the signals travel through to reach us), pulse width comparisons between repeaters and non-repeaters, and rotation measures which is a measure of the magnetized environment of a source.

CHIME's current pulsar monitoring system is one of the top in the world. Because it can observe daily, it is capable of observing timing-array pulsars daily whereas before they could only be monitored every 2-3 weeks. These measurements of timing-array pulsars will be crucial in the eventual detection of gravitational waves through pulsar

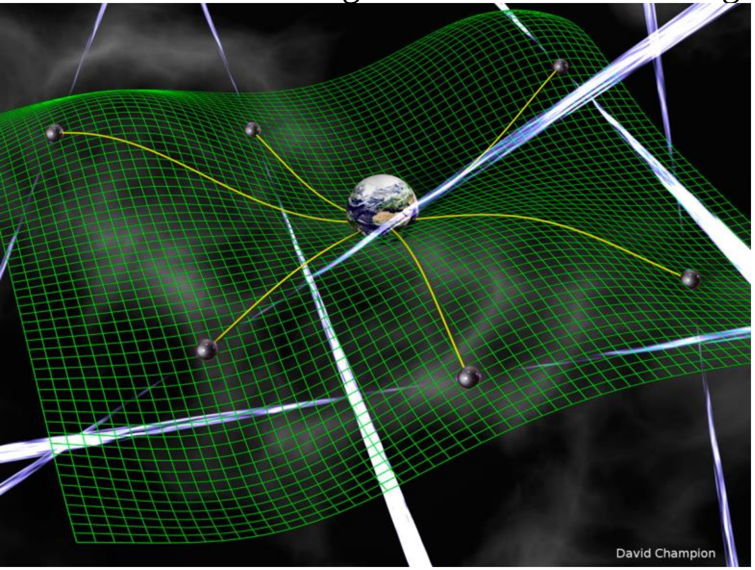


Fig. 10: Pulsar timing array. Signals from pulsars are delayed if a gravitational waves passes between the earth and the pulsar. We can triangulate a gravitational wave signal that likely come from galaxy mergers. [D. Champion]

Conclusions/ Summary:

CHIME is a revolutionary new radio telescope that is a key player in FRB and Pulsar astronomy. It is extremely unique and offers capabilities beyond any other telescope in the world. It is only at the beginning of its lifetime, so there is much more to be discovered.

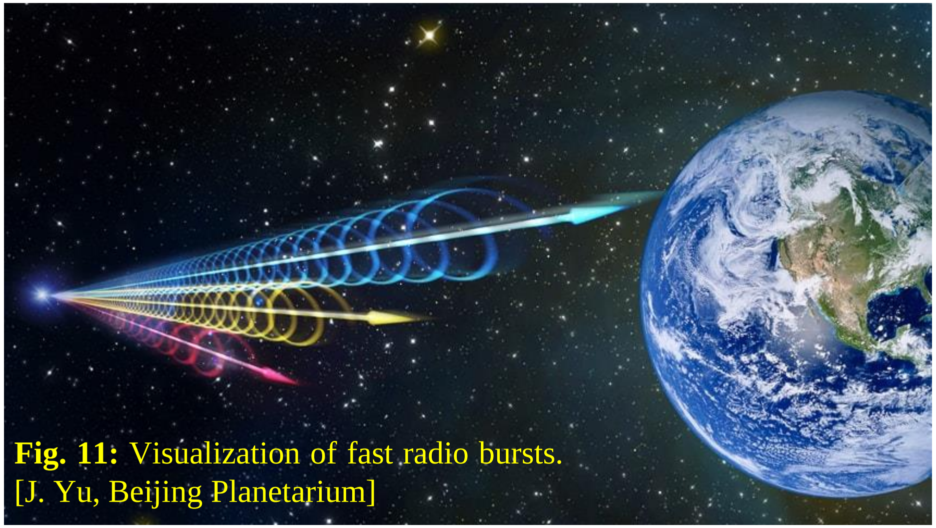
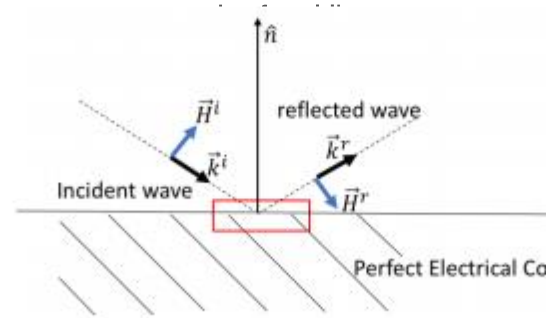


Fig. 11: Visualization of fast radio bursts. [J. Yu, Beijing Planetarium]

FUTURE:

CHIME is a new telescope so there is much more to look forward to. As the only thing limiting the number of observing beams is computation power, CHIME could augment its number of beams significantly. The results from the FRB side are only becoming better and CHIME will most likely be a key player in discovering the source of FRBs. With the recent collapse of the Arecibo, CHIME is also looking to become one of NANOGrav's key telescopes in the detection of gravitational waves.

Physical optics (PO) [26] is widely used in scattering problems at one frequency, which consists of a known incident field and a scatterer with known geometry and electrical properties. The goal is to compute the radiated field from the scatterer with the incident field. Figure 4.4: a diagram showing how plane wave incident on infinite perfect electrical conductor (PEC) is reflected. Imagine a plane wave incident on an infinite perfect electrical conductor (PEC) as shown in Fig. 4.4. It has been well established that the incident angle is the same as the reflect angle, ie ~k i · ~n = ~k r · ~n and that H~ i × ~n = H~r × ~n. (4.3) At the red contour, the Maxwell Equation at frequency ω 5 ×μH~ = 1 c (4πJ~ + jωE~) (4.4) becomes J~ = 1 4π r μ ε H~ × ~n = 1 2π r μ ε H~ i × ~n, (4.5) where J~ is the linear current density. Eqn. 4.5 in theory is only true when the incident wave is plane wave and the scatterer is inifite PEC. Practically, it is very close to real case when scatterer is in the farfield of incident wave 67 and the dimension and curvature of scatterer is larger than five times the wavelength of the Electromagnetic (EM) wave, which is true for CHIME cylindrical reflector. Now with the induced current calculated from Eqn. 4.5, the radiated E field can be easily calculated by A~ = μ 4π Z Z J~ −jkR R dsˆ (4.6) E~r = −jω(A~ + 1 k 2 5 (5 · A~)) (4.7) H~r = 1 μ 5 ×A, ~ (4.8) where A~ is the electric vector potential, R is the distance between the observation point and the source J~ point. The integration in Eqn. 4.6 is over the whole surface of the PEC scatterer. From Eqn. 4.5 to 4.8, the induced current and radiated field are all calculable and programmable and the radiated field acts as an incident field to other scatterers in the system. By this way, with the geometry and electrical properties of the system and the initial incident wave given, the EM interaction within the system can be simulated using PO. The biggest advantage of PO is that it’s a simplification of the Maxwell Equations. Instead of solving all the four Maxwell Equations at every spatial point and time point where EM fields at all the points in the space are entangled, it only solves the problem at the surface of scatters. Moreover, the induced currents are calculated locally at each point. This simplification saves a lot of computation power and time. However, the assumption that the structure simulated is much larger than the wavelength of EM wave is only applicable to the cylindrical reflector in the CHIME telescope, not to



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