HYFAR:

An Array of Cylindrical Reflectors for Precision Cosmology

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Abstract

HYFAR is a proposal for a “Hydrogen Frequency Array” that will study the redshifted 21cm line of neutral hydrogen (HI) from it rest frequency at 1420 MHz down to frequencies as low as 100 MHz, corresponding to cosmological redshifts of 13.

Introduction

HYFAR is an astronomical tool for doing “precision cosmology.” Its principal design goal is to refine our understanding of the dominant constituents of the Universe: the Dark Matter and the Dark Energy.

Cosmologists strive to understand the details of “the cosmological model of the Universe,” a mathematical framework that describes the geometry of the Universe and the rate at which it as expanded as a function of time since the Big Bang. Albert Einstein’s original model had a stationary geometry that required a balance between the attractive gravitational forces, which act to draw the mass in the Universe together, and an additional term, called the Cosmological Constant (labelled by the Greek letter lambda Λ), that Einstein added to his model to make the Universe static. Once Edwin Hubble had observed that the Universe is actually expanding, Λ was set aside, and the big question was whether it would expand forever or would eventually succumb to the attractive gravitational force that might reverse the expansion and lead to collapse (a Big Crunch!).

The precision cosmological measurements of the past decade have produced a surprising discovery [1], showing that the physics of the Universe must be more complicated that we had imagined. Our best cosmological model for the Universe’s geometry has the Universe slowing in its expansion -- as predicted by the gravitational attraction -- during roughly the first half of the age of the Universe; but surprisingly, the Universe subsequently exhibits a re-acceleration, apparently due to an additional pressure (the “dark energy”) that had not been included in serious cosmological models since Einstein’s original lambda Λ.

The new scientific quest is to explore the properties of the dark energy by measuring the strength of the re-acceleration as a function time. This will be accomplished by refining the cosmological model that fits observations of both the nearby and most distant objects in the Universe. HYFAR is a telescope that can perform this measurement.

The Geometry of Space-Time: Standard Rods and Candles

Astronomers use "standard" objects of known dimension or luminosity to measure the geometry of the Universe.

About ten years ago, astronomers observing distant supernovae found hints that pointed to the existence of a Cosmological Constant Λ in the model of space-time.
In an expanding Universe, more distant objects emit spectra of light that are observed at Earth to be increasingly redshifted for more distant objects. More distant objects also appear dimmer, and by measuring the rate of dimming with increasing redshift, astronomers can specify parameters in the mathematical model of the Universe. The supernovae of "Type Ia" are good *standard candles* for these studies, and they point to the existence of non-zero Λ.

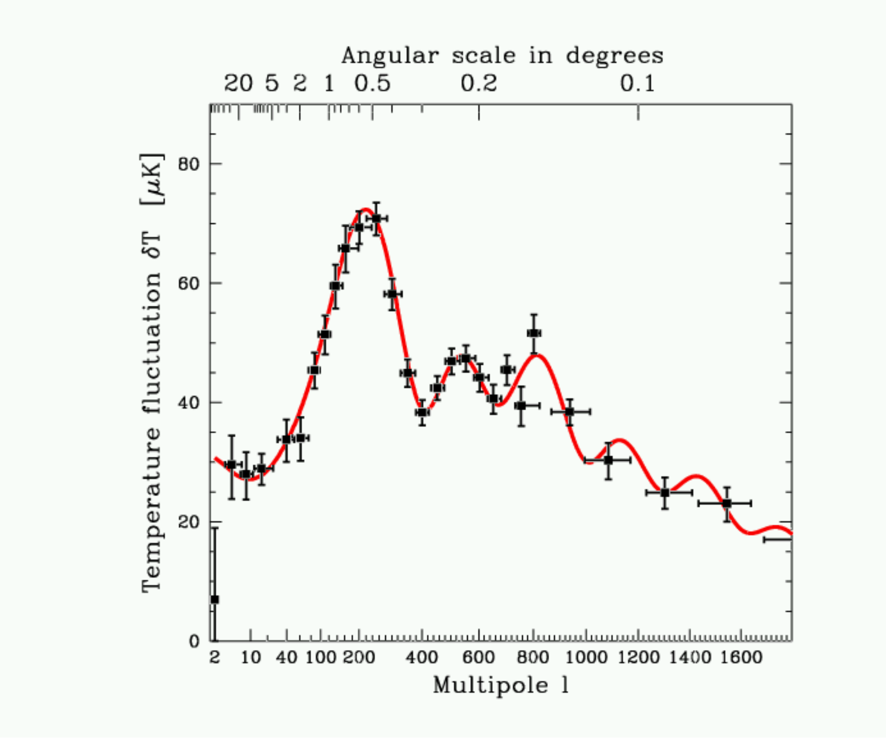

Figure 1. The spectrum of fluctuations in the Cosmic Microwave Background has characteristic scales that indicate the density fluctuations in place at that time (380,000 yrs after the Big Bang, or redshift z=1090)[2]. The angular scale of ~0.5^{o} corresponds to a linear dimension of ~0.1 Megaparsec, which grows with the expansion of the Universe to form the large-scale structure on scales of ~100 Mpc at the present (z=0).

HYFAR will make use of a *standard rod* to specify the geometrical model of the Universe with higher precision than currently possible. Recent studies that combine the Wilkinson Microwave Anisotropy Probe (WMAP) measurements of the cosmic microwave background (CMB) with observations of the large-scale structure exhibited by the clustering of galaxies nearby have confirmed the trend revealed by the supernovae. WMAP, along with other studies of the faint texture in the brightness of the CMB, find a distinct peak at a particular angular scale in the spectrum of the fluctuations of microwave sky. While this angular scale that we observe from Earth at a redshift around 1100 is an imprint of the physical processes that occurred still earlier, the precision cosmological observations rely on this size scale to be a sort of standard rod. In the large-scale structure measured nearby, the standard rod is ~100 megaparsecs in length. The strongest of faint fluctuations in the CMB represent the faint fluctuations in mass density at redshift 1100 that have grown through gravitational instability over time to form the large-scale fluctuations in mass we observe in nearby clusters of galaxies at redshifts near zero.

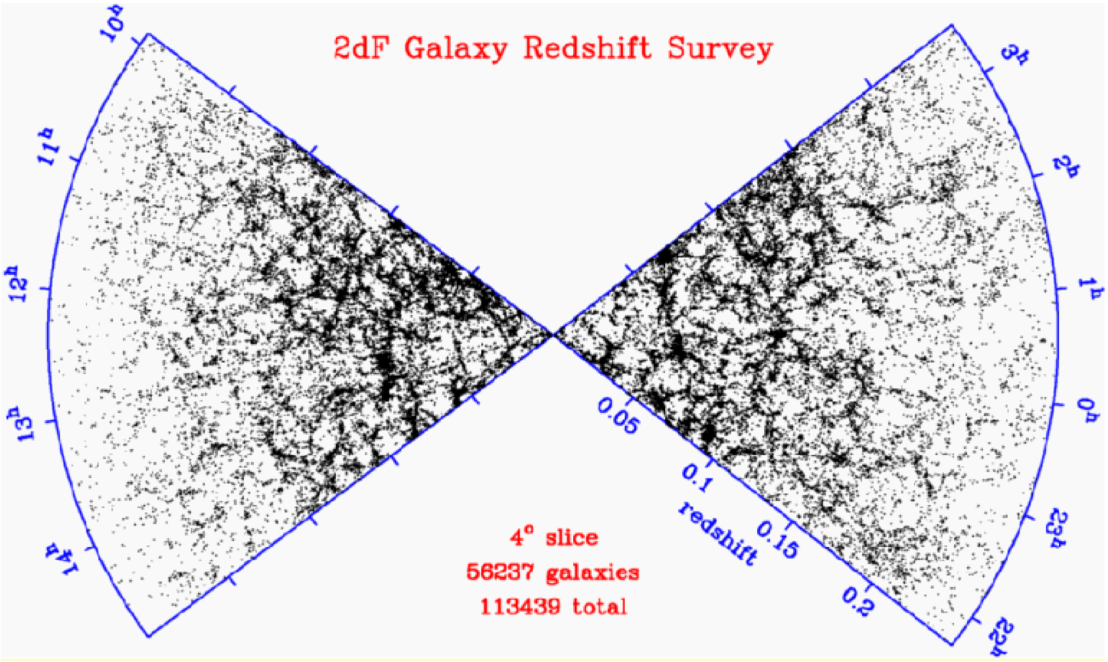

Figure 2. Large-scale structure in the nearby Universe for 56,237 2dF galaxies[3]. A distance of 100 Mpc corresponds to an increment of redshift of $\Delta z \sim 0.025$.

Remarkably, the measures of large-scale structure agree with the measures of supernovae to specify a cosmological model with $\Lambda \sim 0.7$ and mass density $\Omega_M \sim 0.3$ (as a fraction of the critical density), which together produce a "flat Universe" whose curvature term $\Omega_K = 1 - \Omega_M - \Lambda \sim 0$.

Refining the model: Is the Cosmological Constant constant?

Astronomers must perform surveys to measure large-scale structure at high redshift that are comparable in size and space density of galaxies to the local surveys, such as 2dF that has already been made at the AAT at Siding Spring.

To refine the cosmological model further, astronomers need precise measures of the angular size of the "standard rod" as a function of redshift. This will be accomplished by using HYFAR to observe the large-scale groupings of galaxies at several redshifts between zero and the redshift when the CMB was emitted. The optimum redshift for deciding whether Λ is constant turns out to be redshift $z \sim 1$; at this redshift, a galaxy whose hydrogen gas emits radio waves in the 21cm line, must be observed with a radio telescope whose receiver is tuned to $1420/(1+z) \sim 710$ MHz. To gather a sufficiently large number of galaxies to attain the necessary statistical precision, HYFAR must efficiently observe more than 1 million galaxies that are spread over at least 1000 square degrees of sky. The depth of the survey will be Δz~0.1 or more (possibly as great as Δz~0.4, corresponding to an instantaneous frequency coverage of 640 to 790 MHz).

Cosmologists parameterise the properties of the dark energy through the equation of state with $w=p/\rho$, the ratio of the dark energy pressure to its density. A constant Universe has $w = -1$, and the HYFAR observations will focus on deciding whether w as a function of z is constant or not. Figure 3 illustrates the improvement in the measurement of w(z) that is possible with the HYFAR telescope.

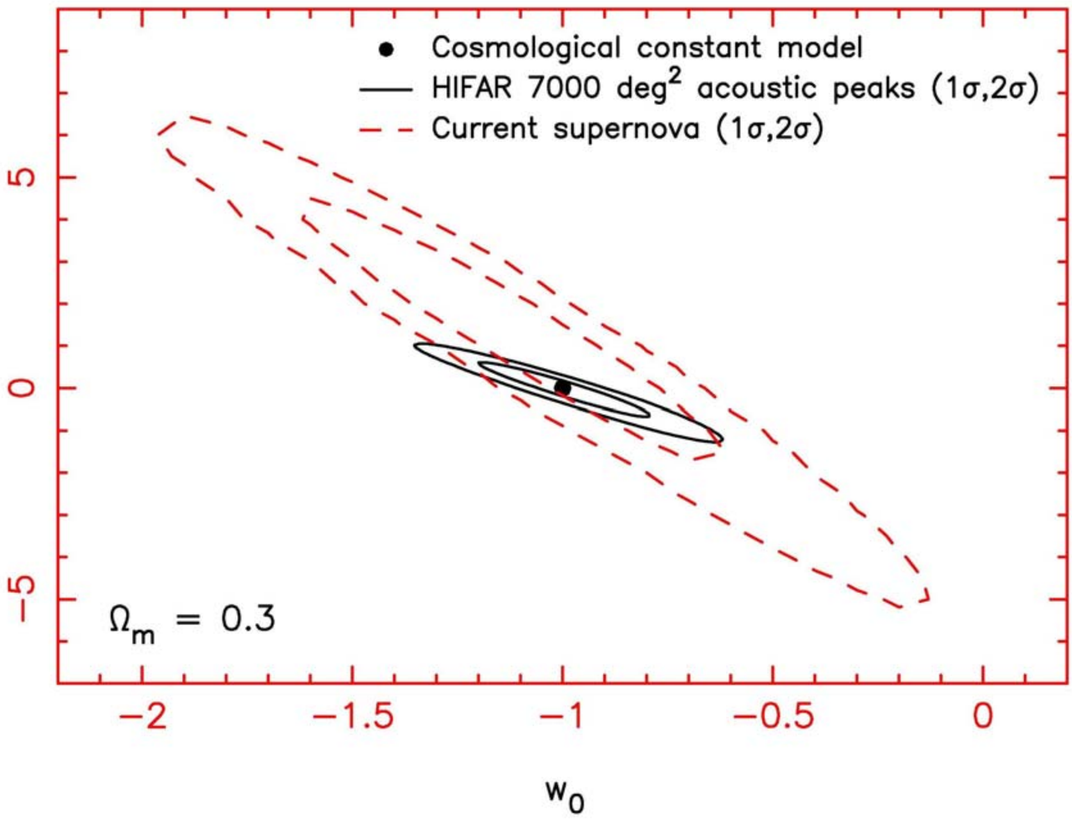

Figure 3. Error ellipses for the measurement of w_0 (constant with z) and w_1 (linear with z) in the expression for the equation of state of the dark energy: $w(z) = w_0 + w_1 \times z$. HYFAR error ellipses are indicated by the black ovals. Current constraints (dashed ovals) extend far outside the boundaries of the plot.

Cylindrical Reflector Concept

At 700 MHz cylindrical reflectors provide an optimum balance between mechanical and electronic cost and complexity while at the same time providing a large field of view that allows rapid surveys of large areas of the sky needed to measure w(z).

Detection of the galaxies by their emission as 21cm at a redshift of z~1 requires a radiotelescope of unprecedented sensitivity. All current proposals for the SKA can survey the 1000 square degrees of sky in less than a year. But we must wait more than a decade for this. A scaled down version of the SKA could also be used but in scaling down the total area by a factor N the time needed increases by a factor of N^2. It is estimate than an instrument with an area 0.2 square kilometres and field of view of 4 square degrees at 700 MHz would take more than 10 years to complete the measurement. Clearly this is no better than waiting for the SKA. The solution to this problem is to build an instrument with 25 times the FOV (Field of View) and reduce the observing time to about year.

Aperture (phased) arrays of dipoles or Vivaldi antennas have a large field of view. But each elemental receptor has an effective area of one sixtieth of a square metre at 700 MHz. Twelve million feeds and front ends are needed to build a 0.2 square kilometre instrument. The scale of the electronics needed makes this uneconomic at this time. The alternative of small parabolic dishes requires about 20,000 units each with an effective area of 10 square metres. Here it is mechanical complexity which is the limiting factor

An approach that reduces the mechanical complexity of the parabolic dish and the electronic complexity of the aperture array is the cylindrical reflector [4] which is parabolic in one dimension and linear in the other. With this approach the incoming electromagnetic radiation is focused onto a line, and a one dimensional phased array (line feed) collects the focussed radiation. The array phasing steers the beam and defines its angular size in one dimension as a function of the wavelength and length of the cylinder. In the other dimension, the diffraction limit of the 15m wide reflector defines the beam size.

Phasing the line feed allows beams to point over a 120 degree arc with no moving parts, while the beam is moved about the orthogonal axis by tipping the cylinder.
For a 15m wide reflector, the field of view perpendicular to the long axis of the reflector is 2 degrees at 700 MHz. In practice it is proposed that three parallel line feeds be used in HYFAR allowing a swathe of sky 6 degrees wide to be imaged at any one time.

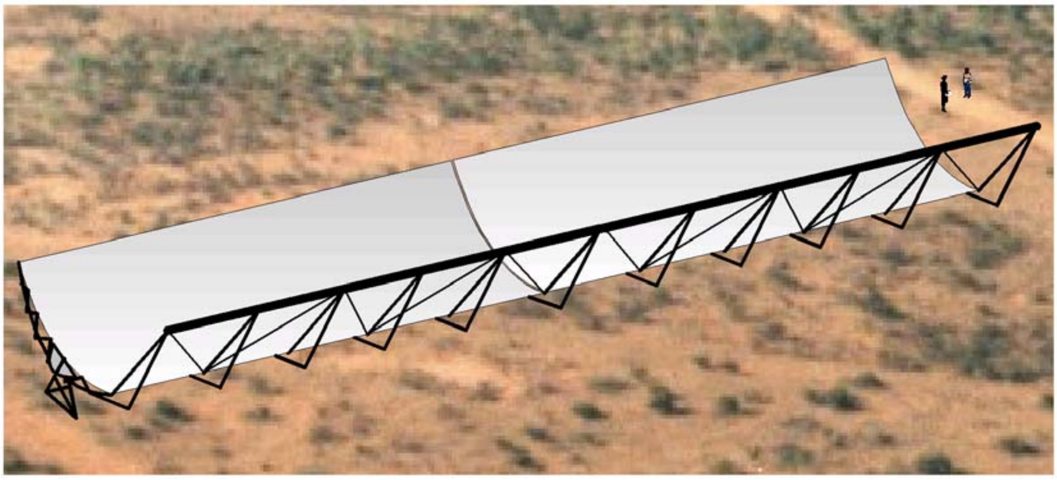

Figure 3 Cylindrical reflector of the type proposed for HYFAR

For HYFAR it is proposed that each reflector is 110m in length by 15m in width. With the 120 reflectors needed to give an area of 0.2 square km there is still some degree of mechanical complexity but it is now reduced to a manageable level. The complexity is further reduced as there is only one axis of rotation in a cylindrical reflector. This also reduces cost, and the estimate for mechanical structures is US$30M in total. For this price every antenna has a mesh reflector with good efficiency up to 1.4 GHz.

Each reflector has a 100m line feed and for operation up to 1.4 GHz a feed element is needed every 10 cm. Thus the full system with three line feeds needs 360,000 feed elements, reducing the electronics cost by a factor of 33 compared to an aperture array. It is estimated that the line feed and associated antenna electronics will cost US$26M.

The angular resolution needed for the 1000 degree survey is modest, and a maximum array dimension of 10 km is sufficient. This allows full bandwidth fibre interconnections to be installed at reasonable cost. This together with the correlator is estimated to cost a further $10M bringing the total cost of HYFAR to US$66M. For this cost an instrument can be built that will answer fundamental cosmological questions and at the same time provide a significant stepping stone to the SKA, both as a cylindrical reflector prototype and as a demonstrator of signal processing at complexities approaching that of the SKA.

Astronomy

HYFAR will be a versatile workhorse for radio astronomy in the 21cm line of neutral hydrogen over the full range of redshifts 0 to 13.

While the timely measurement of the nature of the Dark Energy is driving the design for HYFAR, there are numerous complementary studies both in the redshifted hydrogen line and in the radio continuum where HYFAR will be the world's pre-eminent radio telescope during the period leading to the construction of the Square Kilometre Array.

Hydrogen Line Studies:

1. A HYFAR whose upper frequency limit encompasses the HI 21cm line rest-frequency (1420 MHz) will observe the evolution of galaxies throughout the second half of the age of the Universe. This will include kinematical studies to measure the Dark Matter content of galaxies and clusters, as well as detailed studies of the small HI clouds and dwarf galaxies that slosh around the outskirts of large galaxies, eventually merging to build still more massive systems.
2. Extending the frequency range downward to 100 MHz would permit HYFAR to observe the 21cm line at redshifts up to $z = 13$. This stage of Universe evolution is known at the Epoch of Reionization, when the neutral intergalactic medium is ionised by the first generation of collapsing protogalaxies, whose massive stars emit photoionizing starlight. The collecting area and sensitivity of HYFAR will exceed that of LOFAR in this frequency range.
3. The redshift range $z = 2 – 5$ (frequencies 230-500 MHz for the redshifted 21cm line) is the time period when galaxies grow most vigorously through violent accretion of proto-galactic systems and IGM clouds. The majority of galaxies will fall below the limit for direct detection, but they can be observed in absorption against still higher redshift radio sources. Every line of sight to a high z radio source has a 30% probability of intersecting a neutral-gas-rich system, and HYFAR's high sensitivity will allow a huge increase in the number of suitable background sources.

Radio continuum studies:

1. The large collecting area, compact configuration, and frequency range will be ideal for a wide range of pulsar work. For example, HYFAR is capable of a

pulsar survey with the equivalent of 1000 times the speed of HIPASS. This achieved by a combination of increased sensitivity and field of view.
2. The high sensitivity and modest angular resolution will be excellent for detailed source counts of the weakest radio sources.

Conclusion

The HYFAR concept is an economical and timely approach to tackling some of the most significant current questions in observational cosmology. It will be an important astronomical tool in a wide range of radio astronomical fields in the period leading up to construction of the Square Kilometre Array. Furthermore, the telescope will be an excellent testbed for developing the technologies necessary for the SKA.

References

1. see Seife, C. 2003, Science, 302, 2038, for overview.
2. Spergel et al. 2003, ApJSuppl, 148, 175.
3. Percival, W.J., et al. 2001, MNRAS, 327,1297
4. Bunton, J.D., Jackson, C.A., Sadler, E.M., ‘Cylindrical Reflector SKA’, SKA Design Concept White Paper, 7, July 2002