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Pulsar Observations with Radio Telescope FAST

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Abstract FAST, Five hundred meter Aperture Spherical Telescope, is the Chinese effort for the international project SKA, Square Kilometer Array. An innovative engineering concept and design pave a new road to realizing huge single dish in the most effective way. Three outstanding features of the telescope are the unique karst depressions as the sites, the active main reflector which corrects spherical aberration on the ground to achieve full polarization and wide band without involving complex feed system, and the light focus cabin driven by cables and servomechanism plus a parallel robot as secondary adjustable system to carry the most precise parts of the receivers. Besides a general coverage of those critical technologies involved in FAST concept, the progresses in demonstrating model being constructed at the Miyun Radio Observatory of the NAOC is introduced. Being the most sensitive radio telescope, FAST will enable astronomers to jumpstart many of science goals, for example, the natural hydrogen line surveying in distant galaxies, looking for the first generation of shining objects, hearing the possible signal from other civilizations, etc. Among these subjects, the most striking one could be pulsar study. Large scale survey by FAST will not only improve the statistics of the pulsar population, but also may offer us a good fortune to pick up more of the most exotic, even unknown types like a sub-millisecond pulsar or a neutron star – black hole binary as the telescope is put into operation.

Key words: techniques: radio astronomy — pulsars: general techniques: radio astronomy

1 INTRODUCTION

The Large Telescope, which now is referred to as the Square Kilometer Array (SKA), was proposed at the General Assembly of the International Union of Radio Science in 1993, beginning a worldwide cooperation on this next generation radio telescope. Different technological solutions have been brought forward and studied by institutes participating in the SKA, and will be selected and integrated into the final design. FAST, Five hundred meter Aperture Spherical radio Telescope, to be built in a karst depression in Guizhou province of southwest China is the Chinese engineering concept proposed and extensively investigated since 1994 for realizing the SKA units. Cooperating with Chinese astronomical and engineering communities, the FAST team of the National Astronomical Observatories has successfully conducted studies on the critical technologies including site surveying, an active reflector, a light-weight focus cabin, accurate measurements, advanced control and receivers. So far, the feasibility of the concept has been proven by extensive analysis and prototyping. A demonstrating model at Miyun Radio Observatory of the NAOC is under construction, integrating all results from study phase. The funding proposal of FAST is being submitted to the central government in order to have FAST be selected and built finally as a national mega science facility.

Being the most sensitive radio telescope, FAST will enable astronomers to jumpstart many of science goals, enabling them to explore the space with absolutely new qualities from our home planet to the most distant universe. Among those fascinating subjects, the most striking one could be pulsar studies addressed by this symposium.

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2 FAST SCIENCES IN GENERAL BEYOND PULSARS

The FAST science impact on astronomy will be extraordinary, and will certainly also revolutionize other areas of the natural sciences. Its unique contributions to science may not yet be predictable at present. Followings are some examples from the science case.

The study of atomic hydrogen through the 21 cm line encodes a wealth of valuable information about the origin and evolution of galaxies and clusters of galaxies, the spacial distribution of dark matter and dark energy, the primeval perturbation of the universe, etc. The most distant blind detection of HI clouds by FAST with an interference-free observing period of 1 hour would be able to reach $z \sim 0.7$. For the warm HI shell around an energetic active galactic nucleus, the detection range limit in a moderate integration time was estimated as $z \sim 3$. We have seen a rapid advance in observing results on the geometry of the Universe. WMAP, Wilkinson Microwave Anisotropic Probe, precisely measured the power spectrum through the first special component of oscillation in the CMB, the Cosmic Microwave Background. Interpretation of observation of high redshift supernovae requires an acceleration term in the expansion of the universe. FAST could slice the power spectrum from $z = 0.4$ to $z = 2$, e.g. providing 10^7 redshifts from a large scale survey at $z \sim 0.4$, 10^6 redshifts at around $z = 2$ from a deep survey of some 10 s square degrees. Within this ranges, FAST survey will allow the time dependent effect of dark energy as function of redshifts, to be measured with an accuracy better than 0.1 per redshift bin, which may help in discriminating among different Λ-CDM (C…D….M…) models.

The capability over other instruments in radio quiet environment, huge effective area without diffraction constraints at low frequencies, low sidelobe level compared with a dipole array, and day-1 receivers promises FAST a powerful tool probing into high-z universe. According to the theoretical predictions of the physical characteristics of the reionization, we also expect FAST may have a good fortune to determine the precise epoch of re-ionization, the EoR.

There are two 25 m antennas of the European VLBI Network in China. The largest element is 100 m in the world VLBI networks, being as Effelsberg and the newly built GBT. Because of the large collecting area and its geographic location at the edges of all networks, FAST will increase the long-baseline detection sensitivity by an order of magnitude. The number of radio sources imageable by VLBI would be enlarged by 3 orders of magnitude. The telescope will play an important role in future VLBI observations. A 10 m space antenna combined with ground stations including FAST will yield a sensitivity increased by a factor of 5$\sim$10 compared with the previous space VLBI program. Having a spacial resolution much smaller than the Sun-earth distance for nearby objects and the highest sensitivity ever achieved, this system may be able to resolve the fine structures of weak thermal sources, to get a close up of the origin and evolution of stellar sources, even to directly image the radio loud extrasolar planetary systems.

Up to 2004, 123 molecular species have been discovered in vast interstellar clouds of dust and gas. This revised chemical evolution history of earth life – our planet orbits in a space contaminated with the seeds of life. Among these molecules, 8 kinds emit far more energy than expected under certain condition, which turns out to be the great discovery of the maser, microwave amplification by stimulated emission of radiation, in space. There are 50 more non-thermal maser emission lines which have been detected in thousands of molecular clouds in our galaxy. About 20 percent of molecular lines are observed in centimeter and decimeter bands. The operating frequencies of FAST cover 17 lines, including hydroxyl, methyl alcohol, formaldehyde, etc. FAST is able to make deep surveys of the molecular masers in our galaxy, in bright infrared galaxies, high redshift galaxies, and other active galaxies. No single methyl alcohol maser has been detected yet in extragalactic systems. The high sensitivity and wide sky coverage of FAST could be expected to produce a breakthrough in this discovery.

FAST will play pivotal role in bioastronomical studies. Joining ground DSN support, it is able to increase the tracking capability at low frequency which is critical during the turning and landing processes of the spacecrafts of the planetary exploration missions. FAST can be aimed at those known planets outside the solar system to detect the line emission of various compounds such as methane (CH_4) which is being considered as potential biomarkers for surface life. An alternative approach is to search for the evidence of alien technology – Search for Extra-Terrestrial Intelligence. By virtue of the fact that radio emissions from the Earth make it detectable over interstellar space, a natural strategy is to search for the artificial signals. To meet extraterrestrial communicative society, radio wavelengths offer a number of advantages, especially, in the range 1.42 GHz hyperfine transitions of the neutral hydrogen and 1.65 GHz due to the OH radial which is referred to as the water-hole by SETI scientists. This window is precisely located at the center of the core band of the FAST on which multi-beam feeds and day-1 receivers are to be equipped at the frequencies. Being the most sensitive tool for SETI, radio telescope FAST will be able to search for "leakage" signals from other civilizations in a much larger volume than has been possible so far.

3 PULSAR SCIENCES WITH FAST

The discoveries of pulsars and binary pulsars, identifying the rotating neutron star and verifying the existence of gravitational waves, won the Nobel Prizes for physics in 1974 and 1993. There are more than 1750 pulsars which have been discovered, including 170 more millisecond pulsars and 25 extragalactic pulsars. Neutron stars are among the most exotic of known astrophysical objects, and present unparalleled laboratories for fundamental physics.

The theoretical prediction of the number of observable pulsars in the galaxy is $\sim$70 thousands, less than 3 percents of which have been detected so far. As the sample is rapidly expanded mostly by large-scale surveys, many new types of pulsars were discovered such as millisecond pulsars, binary system, pulsar with a massive companion, pulsar with a planet, X-ray pulsar, γ-ray pulsar, etc. The recent discovery, double pulsar binary PSR J0737–3039A/B (Burgay at el. 2003; Lyne et al. 2004), shows a short orbital period of 2.4 h and highly relativistic orbiting velocities which are speeding up the coalescence process of the two neutron stars. To capture such events may provide the international community of gravitational wave detection a unique opportunity for testing the predictions of General Relativity. These new discoveries demonstrate that some of most interesting species may yet wait for detection from large scale surveying.

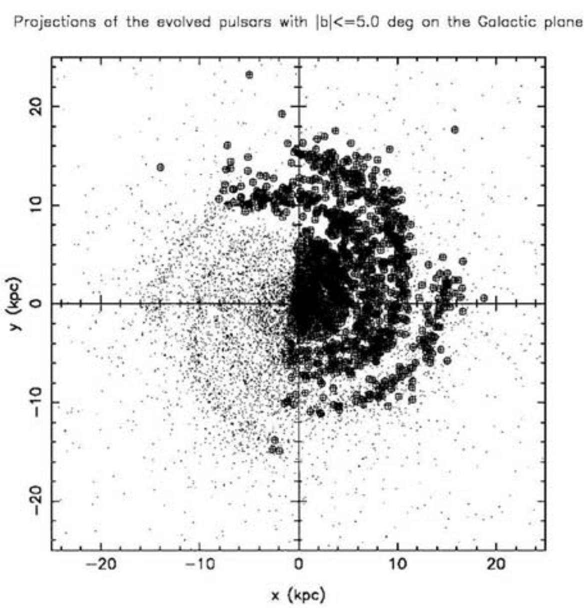


Fig. 1 FAST pulsar survey coverage.

High sensitivity and large sky coverage make FAST a powerful tool for detecting those weak emissions from pulsars at large distances. It is estimated that FAST equipped with multibeam receivers and focal-plane-array feed in future would detect some 7000 pulsars in less than a year of observing time (Fig. 1). The discovery would not just improve the statistics of the pulsar population, but it may pick up more of the exotic, even unknown types like a sub-millisecond pulsar, a possible candidate of 'strange' star (Zhou et al. 2004), or a neutron star - black hole binary, a direct evidence of black hole without model dependence. The high raw sensitivity of FAST will certainly help in understanding the complex radiation process by observations of individual pulses, microstructures, polarization, etc.

Millisecond pulsars are rotationally very stable. Observations of some millisecond pulsars have shown long term stability comparable to or better than atomic clocks. And the longer it is monitored, the more precise timing information one can get. More than 10 Pulsar Timing Arrays (PTA) (Manchester 2006; Stapper 2006) have been put in use, establishing a new time standard which is independent of the current atomic time standard. With its large collecting area and the new generation of pulsar receivers, FAST may increase the precision of the time-of-arrival (ToA) measurements of millisecond pulsars from the current hundreds of ns down to tens of ns, and a FAST PTA may also enlarge the number of millisecond pulsars from recently less than 20, to 100, contributing to this new timing standard effort. *http://www.ligo.caltech.edu/∼kent/ASIS_NM/enhanced.htmlhttp: //www.srl.caltech.edu/∼shane/sensitivity/*

We obtain the astrometric and physical parameters of pulsars by long term and precise ToA measurements. If we know these parameters like position, proper motion, timing model of a group of pulsars, on the contrary, we may expect to measure tinny variation residuals of ToAs with a time scale longer than years. These timing residuals may enable the direct detection of gravitational waves (GW) (Estabrook & Wahlquist 1975; Sazhin 1978; Detweiler 1979; Fredrick et al. 2005). This PTA work has been considered and/or carried out already by several pulsar research groups. Ground LIGO waits for the coalescence of the two neutron stars, while the future space mission, the LISA, is expected to bring the first light of GWs from Galactic binary systems 2 years late(?). FAST may provide the most precise observations of ToAs, therefore, may largely increase the sensitivity and widen the spectral window for detection of GWs from massive black hole pairs or the Big Bang as shown in Figure 2.

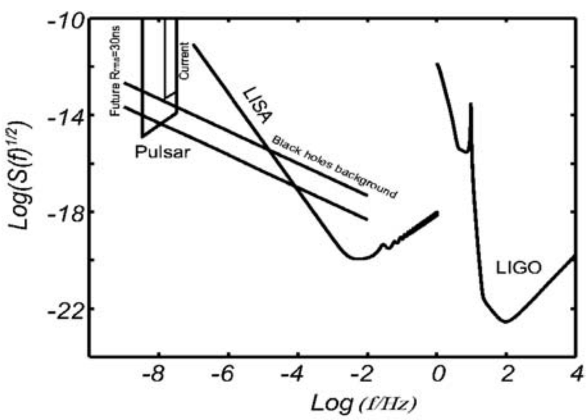


Fig. 2 This figure shows spectrum of binary black hole GW background and the sensitivity of several kinds of GW detectors, including the simulated PTA using FAST. In the simulation, the present pulsar timing RMS noise is assumed to be 120 ns, while the FAST timing RMS noise is 30 ns. The black hole GW background prediction is derived from Jaffe and Backer 2003 [2].The LISA and LIGO data are public official data (LIGO data site: *http://www.ligo.caltech.edu/ kent/ASISd_NM/enhanced.html*, LISA data site: *http://www.srl.caltech.edu/ shane/sensitivity/*). It can be seen that FAST may be able detect the GW background from binary black hole within 5 to 10 years time (figure provided by K. J. Lee.)

Deep space navigation based on pulsar ToA measurement will be an entire autonomous technique. This technique may become an ideal method to be used for autonomous navigation far away from the earth. With its enormous collecting area, FAST may greatly enhance the precision of the ToA measurement, thus may be able to contribute in building up a better pulsar timing model database to be used for future navigation work.

4 ENGINEERING CONCEPT AND DEMONSTRATOR

Figure 3a shows three outstanding features of telescope FAST: the unique karst depressions found in Guizhou province as the sites, the active main reflector of 500 m which directly corrects for spherical aberration on the ground, and the light-weight focus cabin driven by cables and a servomechanism plus a parallel robot as a secondary adjustable system to carry the most precise parts of the receivers. FAST will cover a frequency range of 0.13∼5 GHz. And it will be equipped with a variety of terminals for different scientific proposes. The optics of the telescope is illustrated in Figure 3b.

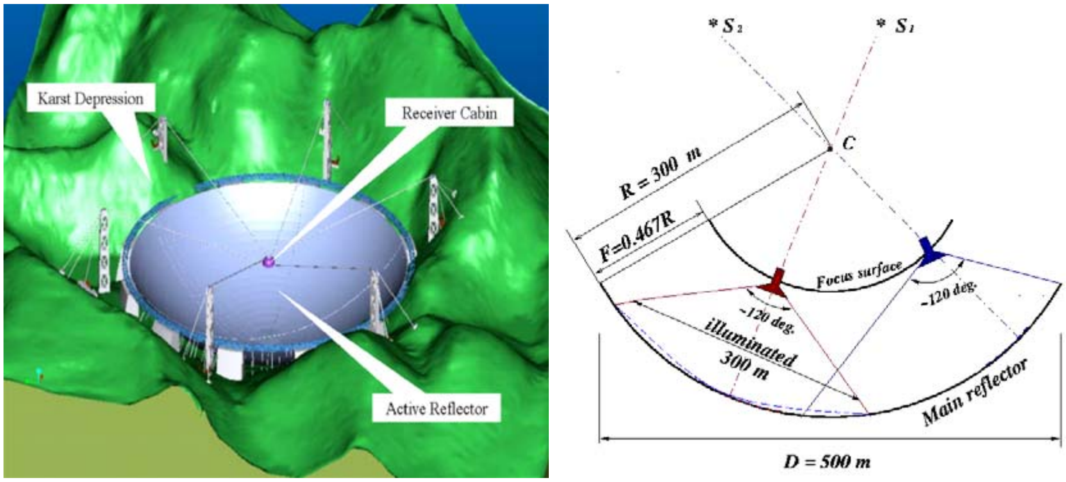
Studies on key technologies of FAST engineering concept were started in the NAOC in 1994. Relevant R&Ds include site surveying in Guizhou province, modeling the active reflector and light feed support, investigating accurate measurement and advanced control technologies, and receiver layout design. This study was selected and supported as one of the key projects of the Chinese Academy of Sciences in 1999. Feasibility of the concept was reviewed and approved by a committee of experts recommended by the CAS in 2001. In order to further confirm and optimize these key technologies, a 50 m demonstrator integrating the indispensable elements is being constructed now at the Miyun Radio Observatory of the NAOC.

The 50 m demonstrator consists of active main reflector, feed positioning, receiver and MAC (Measurement and Control) subsystems. The reflector subsystem consists of an artificial cement depression, cable actuators, cable network, nodes, panels and a girder ring (Fig. 4). The depth of the cement depression is 5.5 m, consisting of 6 stairsteps. On the cement surface, cable actuators are mounted. This cable servomechanism is attached to the ground anchor through an adjustable structure, which enables to turn actuator along azimuth and elevation directions in order to point its axis to the spherical center of the reflector. The back structure of the main reflector is a cable network made from steel cables joining adjacent ones through nodes. The rim of the network is fixed on the girder ring through adaptive joints. Triangular panels are installed on the top of nodes. Each node is linked to the actuator through down tied cable driven by servomechanism during the reflector deformation. A delicate adaptive connection was designed for connecting the panels and the nodes, this enables adaptive compensation for small changes in the spatial distance between panels during deformation without involving any extra control.

The feed positioning system includes four towers, trolley and Stewart stabilizer, has been built for pointing and tracking the telescope model. The cable track of the trolley is built by two crosswise sets of cables suspended on two pairs of opposite towers. Four active cables drive the trolley along the cable track during the observation. The driven cables provide a coarse control of the motion of the upper platform of the Stewart mechanism, while the Stewart mechanism give a finer control of lower platform where the receivers are mounted by actively isolating the vibrations from the upper platform. Tension feedback is applied to avoid the relaxation of the cables. Standard PID controllers with direct terminal feedback from the optical position sensors are employed to realize the close loop control.

In order to achieve precise measurement and control of the main reflector deformation and feed positioning, a common well-defined reference system has been set up for the experiment of the demonstrator. Four concrete columns of 1.25 m in height are built at the four corners of the field, these are used as the datum mark for calibration of the coordinates of the ground anchors. Three concrete towers are erected around the main reflector, acting as pedestals for the laser total stations as the measurements are carried out. During observational experiment, three of six total stations are to be used to measure the position and orientation of focus cabin, while the others total stations can be used to survey the positions of 131 nodes on the main reflector. An alternative option for measuring the reflector is to monitor the length variation by the encoders equipped on the actuator, which can only realize an half close loop control. A field bus technology, named as CAN, is applied for communications between main control computer and the actuators.

Astronomical observations have been considered by using this FAST Demonstrator. This demonstrator may work up to S band. Due to the limited space and weight load, we may only use room temperature receivers. The effective collecting area of this demonstrator would offer enough sensitivity for certain observations, such as bright pulsars, neutral Hydrogen (HI) line and some luminous AGNs. We plan to carry out pulsar observations at 610 MHz and 1400 MHz. The L-band receiver could also be used to observe the galactic HI line. We browsed the ATNF pulsar catalogue (Manchester et al. 2006), and find that there are at least 8 pulsars could be readily detected with integration time of several minutes up to 30 minutes. The beam width of this demonstrator is about 50 arc minutes, and the system temperature at L-band is about 120 K. For resolution of 10 kHz, we may readily detect 10 K HI emission line with integration time of 1 second. These observations may help to illustrate an overall performance of the demonstrator as a working radio telescope.



(a) (b)

Fig. 3 (a) FAST 3-D model; (b) The optics of the telescope.

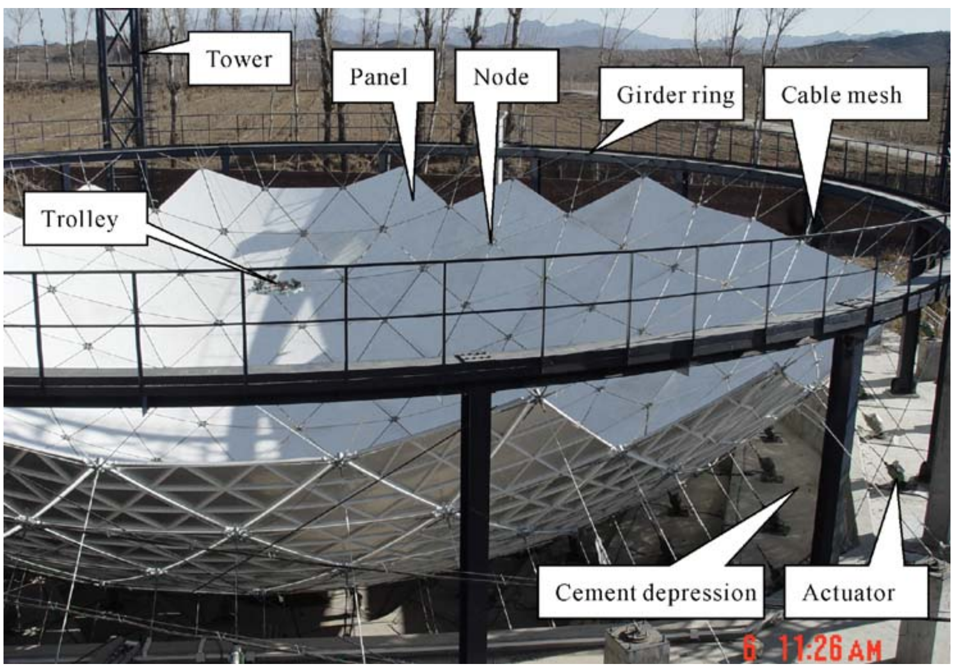


Fig. 4 Miyun 50 m demonstrator of FAST under construction.

5 CONCLUSION REMARKS

FAST is the largest radio telescope in the world. Pulsar research is one of its key science objectives. We plan to equip it with state of the art multi-beam receivers at its core band - L band. This, combined with the still very quiet radio environment, makes FAST an ideal tool for pulsar research. Observations using FAST may greatly enlarge the pulsar population, which may result in discovery of more exotic type of pulsars or even a neutral star – black hole binary. FAST may greatly increase the precision of pulsar ToA measurements, this may lead to better timing models for pulsars. By monitoring a group of millisecond pulsars, FAST may help in detecting of GW background, and perhaps also a timing standard based on highly steady rotation of millisecond pulsars. We are preparing for the expected and unexpected scientific results that might come from the FAST in the future.

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