This paper will serve as a broad overview to past and recent observations of the objects left behind by core collapse supernovae; namely neutron stars, pulsars, and magnetars. I will focus mostly on the aforementioned object's peculiar velocities and the methods by which they could have been “kicked.” Since pulsars are observed to exhibit velocities much higher than those of their likely progenitors it is assumed that a kick must be provided to them during formation. Possible kick mechanisms such as hydrodynamic, magnetohydrodynamic, and electromagnetic are compared to observations. Correlations between kick direction and spin axis orientation, as well as magnetic field strength and kick velocity are then investigated. The accompanying powerpoint presentation contains all relevant figures and is referred to by slide number.

TALK I INTRODUCTION

Core collapse supernovae represent the last stages in the life of high mass stars. Stars above the Chandrasekhar limit of ~1.4 solar masses will undergo a supernova once nuclear burning at their core can no longer support the mass of the star from gravitational collapse (Slide 2 shows the life cycle of a high mass star leading to either a black hole or a neutron star remnant). The outer layers then collapse and rebound off of the star's massive core (slide 3) releasing energy on order of $10^{53}$ ergs. Type I supernovae (slide 4) are a thermonuclear explosion caused by accretion beyond the Chandrasekhar limit of one of the components. Neutron stars are not left behind by these events, however neutron stars can exist in binary systems.

Neutron stars left behind by core collapse supernovae are sometimes observed as pulsars. The star's spin axis is usually offset from its magnetic dipole and as the star rotates a beam of radiation associated with the dipole moment is seen as a regular pulse of radio waves along a particular line of sight (slide 5). Pulsars are generally observed to have proper motions between 200 and 500 km/s with some traveling as fast as 1000 km/s. This is much faster than the velocities of their progenitors which can be assumed to average ~10 km/s (Lai 2000), implying that neutron stars undergo some form of kick during formation. The currently observed population of pulsars can be described as an exponential distribution with a scale height of 330 pc in the galaxy (Lorimer et al 2006). About 20% of pulsars have velocities faster than the escape velocity of the galactic gravitational potential, so some kicks are strong enough to eject the neutron star from the galaxy entirely.

Many possible mechanisms have been proposed for the origin of these kicks, however it is still not clear which of these dominates the observed kicks in the galaxy. This paper seeks to investigate past and current work on the subject of neutron star kicks and clarify the differences between the kick velocities. Since this paper mostly follows the accompanying powerpoint presentation it is laid out as such. First I will discuss the three main kick mechanisms, then compare these to some observations and look to the Crab nebula pulsar as a specific example; then the second talk reviews the kick mechanisms and looks into comparisons with more recent observations.

KICK MECHANISMS

The kick that provides a neutron star's velocity must be extremely strong. While it is possible that a
binary system could be disrupted during a core collapse supernova, the breakup of a binary system is not sufficient to produce the peculiar velocities observed for pulsars. The kick mechanism must occur during the supernova that forms the neutron star. Since energies of $\sim 10^{51}$ ergs are observed during these events, the asymmetric emission of energy (most of which comes in the form of neutrinos) during a supernova could produce the required kick. The two mechanisms that could produce such an asymmetry are Hydrodynamically driven kicks and Neutrino-magnetic field driven kicks. Conversely, the kick could come as a push after the neutron star is formed since pulsars are observed to emit in a preferred direction. This method is referred to as the Electromagnetic rocket.

**Hydrodynamically driven kicks (slide 8)**

Kicks that arise due to hydrodynamic asymmetries in the progenitor star can produce the high velocities observed in the neutron star population. The instabilities must be present prior to the star's collapse in order to produce the high velocities. If there is some small instability in the core of the progenitor, oscillations of the core can ensue and become over-stable (driven) by asymmetric thermonuclear burning (Goldreich et al 1996). As the core oscillates the gas on the leading side of the core is compressed, increasing the temperature and triggering more thermonuclear burning; this pushes the core back and produces the same effect on the other side, thus driving the oscillation. Eventually the core will undergo a supernova and as it collapses the asymmetric density will cause the emission from the supernova to be asymmetric and kick the resultant neutron star.

This mechanism doesn't require an extremely strong magnetic field, or necessarily imply that the kick direction and the neutron star's spin axis will be aligned (Lai 2000); however if the star experiences a few short period kicks via hydrodynamic asymmetries on a timescale shorter than the star's rotation period, spin-kick alignment can be produced (Wang, Lai, & Han 2007).

**Neutrino-magnetic field driven kicks (slide 9)**

Interactions between the neutrino emission and the star's magnetic field can produce asymmetric kicks in a few different ways. Since most of the energy emitted by a core collapse supernova is in the form of neutrinos, these methods can produce the strong kicks required for high velocities. The first is via parity violation. Since the opacity of the medium through which the neutrinos travel is dependent on the neutrino's momentum vector with respect to the magnetic field, an asymmetric magnetic field can induce asymmetric opacities and therefore asymmetric emission of neutrinos. In addition, the absorption cross section of neutrinos is dependent on magnetic field strength. So not only the directionality of the magnetic field can cause asymmetric emission, but asymmetries in magnetic field strength across the star can lead to kicks. The final method has asymmetric magnetic fields suppressing convection in the progenitor star causing dark spots (akin to sun-spots) of neutrino emission. These asymmetries of emission can provide the kick needed.

Difficulty in supporting these mechanisms comes when the magnetic field strength required to produce strong enough kicks is considered. In order to produce the velocities observed the progenitor magnetic field around these stars would have to be of order $10^{15}$ G. While these strengths are possible and observed for objects such as magnetars, generally magnetic fields around both neutron stars and their progenitors are much weaker (Lai 2000). Like the Hydrodynamic mechanism, neutrino-magnetic field kicks can, but do not necessarily produce spin-kick alignment. One would expect this method to produce some correlation between magnetic field strength and kick velocity.

**Electromagnetic rocket (slide 10)**

The final kick mechanism actually takes its effect after the supernova occurs. Since the neutron star's magnetic field can be slightly misaligned to the spin axis of the star the rotating magnetic field will
emit electromagnetic radiation as the star spins down. The energy emitted comes from the angular momentum being removed from the star as its period increases. This mechanism naturally produces spin-kick alignment since the radiation is emitted along the star's spin axis.

In order to achieve the high velocities observed in the pulsar population, initial rotation frequencies would have to be on the order of kHz. Additionally, the magnetic field strengths required by this method are also quite high (again of order $10^{15} \text{ G}$) in order to spin the star down along a short enough period to kick the star sufficiently (Lai 2000). So for this to be the dominant kick mechanism, one would expect to observe spin-kick alignment as well as a correlation between magnetic field strength and kick velocity.

INITIAL COMPARISONS TO OBSERVATIONS (Slide 11)

According to Cordes & Chernoff (1998) the current population of pulsars shows no correlation between magnetic field strength and pulsar velocity. Most pulsars are observed to have magnetic fields of $\sim 10^{12} \text{ G}$ though these could have been stronger initially and decayed with time (Lai 2000). Cordes & Chernoff also do not see any convincing evidence for spin-kick alignment, though this is not ruled out due to insufficient data. These comparisons will be re addressed with newer results later in this paper when I describe the second talk.

SPECIFIC CASE: CRAB NEBULA

The Crab Nebula and its associated pulsar provide a unique case to examine in an attempt to understand neutron star kicks. Since the Crab Nebula is so young and nearby, much is known about it that can only be inferred for other pulsar/supernova remnant associations like its exact age and spin axis direction. The supernova that created the Crab occurred in 1054 and was observed and recorded by astronomers and people around the world, giving astronomers today an advantage in measuring the pulsar's velocity. Unfortunately, distance measurements to the pulsar are somewhat uncertain, creating difficulty in measuring an accurate velocity. According to Kaplan et al. (2006), assuming a distance of 2 kpc the pulsar has a velocity of 120 km/s and is moving about $14^\circ \pm 2^\circ \pm 9^\circ$ (errors for transverse and radial directions respectively) offset from its spin axis.

Since the distance measurement to the nebula is quite uncertain, precise determinations of velocity and offset angle are difficult. The radio flux from the nebula prevent accurate interferometric measurements of the pulsar and nearby background stars for parallax are also mostly blocked by the remnant. Despite the uncertainties future observations of the Crab Nebula and its pulsar could shed more light on neutron star kick mechanisms, as of now though it does little to single out one specific model.

TALK II INTRO

I refer the reader to the above section on kick mechanisms as an introduction to the second part of the paper focusing on the second talk. This part goes into more detail with respect to recent analysis of spin-kick alignments and strong magnetic fields around pulsars. After addressing these correlations I bring up the topic of magnetars, or highly magnetized neutron stars, and implications of their observations as anomalous X-ray pulsars and soft gamma-ray repeaters. These generally have much slower rotation periods than radio pulsars and much stronger magnetic fields, but are assumed to be a similar object.

SPIN-KICK ALIGNMENT
Wang, Lai, and Han (2007) analyzed the transverse velocity directions of the current known population of radio pulsars and compared those with the direction of polarization of light from the pulsar. Since the neutron star's magnetic field will be closely associated with the spin direction (though not exactly aligned) one expects that radiation from the pulsar will be polarized at either 0° or 90° to the spin axis (to match the magnetic field). One can see from the plot on slide 19 that their analysis shows two distinct peaks of transverse velocities centered around 0° and 90° which provides distinct evidence of spin kick alignment.

While each of the kick mechanisms can produce spin-kick alignment under the right conditions (namely kick timescales shorter than the rotation period for hydrodynamic and neutrino-magnetic field kicks) and the EM rocket mechanism produces it naturally, simulations to recreate the observed distributions fit best with the hydrodynamic mechanism. The strong magnetic fields required by the other two methods are not observed, and a lack of an observed spin-kick alignment of the population of pulsars in binaries support this conclusion.

**MAGNETIC FIELD STRENGTH AND KICK VELOCITY**

As can be seen by the plot on slide 20 (Itoh & Cotuda 1994) any correlation found between magnetic field strength and kick velocity is quite dubious. Further inspection reveals that any correlation can be accounted for by a selection effect. Since pulsar surveys are biased against very distant sources, the older high velocity sources, which may have left the plane of the galaxy, are difficult to detect. These sources would presumably have weak magnetic fields and their absence in a survey could create the illusion of the fastest sources having the strongest magnetic fields (simply by virtue of being the youngest). A simulated population of pulsars confirms that the correlation observed can be explained by this selection effect.

**MAGNETARS**

Since there is no correlation observed between magnetic field strength and velocity of regular pulsars, it may be interesting to consider the population of neutron stars that have extremely strong magnetic fields, or magnetars. Magnetars generally have field strengths ~10^{15} G. They are observed as anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) which, as their names imply, are periodic sources observed in the X-ray and gamma-ray bands respectively. These are generally observed with periods of ~5-12s (much slower than radio pulsars) and only 11 sources have been detected to date (Gaensler 2004).

Since so few have been detected, it is extremely difficult to draw any conclusions about the overall properties of the populations. Ideally, the supernova remnants associated with these sources could be located and transverse velocities could be determined. Attempts to locate the associated SNRs for these sources have mostly come up short. Since the sample set is so small, nothing is really known about what velocities these objects should have. And since their periods are quite slow and erratic, the standard method of determining a pulsars age $t = P/(2(dP/dt))$ provides no useful information. Without knowing how old these objects are or having any expectations about them, the only way to associate a SNR with one is to observe one near to it. This is difficult because the odds of a false association are quite high. One needs only to consider the probability of an SNR being on the line of sight with the object (distances for these objects are highly uncertain) to realize how little can be assumed about any claimed association. The only associations that can be taken seriously are where the object lies near the exact center of the SNR, the likelihood of this happening by chance alignment is extremely small. Of these associations, transverse velocities tend to be $\leq 500$ km/s and have ages of $\sim 10^4$ years (as determined from the remnant).
These associations tell us little about the general properties of these objects with such a small sample, but hopefully future detections will shed more light. It could be that the magnetar kick mechanism is entirely different from that of pulsars. Since there is no reason to believe yet that magnetars all have extremely high velocities, many SNR associations could be overlooked. If this is the case then the mechanisms that require high magnetic field strengths could be dominating this population. As of now though there is little reason to believe that AXPs and SGRs are anything other than a young, highly magnetized population of neutron stars.

CONCLUSIONS

While current observational constraints limit what we can garner about neutron star kicks, headway is consistently being made in the field. As of now evidence points to hydrodynamic oscillations being responsible for core collapse asymmetries, but future observations of magnetars could provide evidence for the dominance of other kick mechanisms in this population. This paper sought to introduce the reader to neutron star kicks and their associated questions. The following references should be useful as a kicking-off point (pun intended) to looking further into the field.

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