Young Collapsed Supernova Remnants: Similarities and Differences in Neutron Stars, Black Holes, and More Exotic Objects

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Abstract. Type Ia supernovae are thought to explode completely, leaving no condensed remnant, only an expanding shell. Other types of supernovae are thought to involve core collapse and are expected to leave a condensed remnant, which could be either a neutron star or a black hole, or just possibly, something more exotic, such as a quark or strange star, a naked singularity, a frozen star, a wormhole or a red hole. It has proven surprisingly difficult to determine which type of condensed remnant has been formed in those cases where the diagnostic highly regular pulsar signature of a neutron star is absent. We consider possible observational differences between the two standard candidates, as well as the more speculative alternatives.

We classify condensed remnants according to whether they do or do not possess three major features: 1) a hard surface, 2) an event horizon, and 3) a singularity. Black holes and neutron stars differ on all three criteria. Some of the less frequently considered alternatives are “intermediate,” in the sense that they possess some of the traits of a black hole and some of the traits of a neutron star. This possibility makes distinguishing the various possibilities even more difficult.

INTRODUCTION

Almost by definition, all supernovae leave an expanding remnant of their explosion, and these expanding remnants are the prime focus of this conference. In addition at least some supernovae leave a condensed remnant which is of interest in its own right, and which may also strongly influence the larger expanding remnant. We focus here on these condensed remnants. Typically, three alternatives are considered: a neutron star, a black hole, or no remnant at all. Type Ia Supernovae are thought to leave no remnant, but all other types are expected to leave either a black hole or a neutron star. However, other types of collapsed remnants have been considered by many authors. Among them are quark [1,2], strange [3–6] and boson stars [7,8], soliton stars [9], frozen stars [10–12], naked singularities [13,14],
and wormholes [15–17]. Other, less well-known, possibilities include a type of object Mitra calls an eternally collapsing object (ECO) [18], and a somewhat similar object that I have discussed previously and called a red hole [19], but am now beginning to call a “big red bag,” because this latter term is more descriptive. In this brief conference poster summary, we will not go into the theoretical motivations for considering these more exotic objects, nor into their technical definitions. Instead, we will provide generic, phenomenological descriptions of these different types of object, and consider how they might be detected or rejected by observations of supernovae and especially of their condensed remnants. In most cases, these same techniques are used to detect the difference between neutron stars and black holes, and to constrain certain properties of the condensed objects, such as neutron star equations of state.

The primary purpose of this paper is to urge that alternate models of condensed remnants not be overlooked, and to point out that standard models are already experiencing some difficulties explaining the observations. Several significant observational constraints are already in hand and more are in the offing. The second purpose is to suggest, and partly demonstrate, that both the theoretical models and the observational constraints can be expressed in terms of largely theory-free phenomenological parameters, for standard as well as more exotic objects.

**TRIPARTITE CLASSIFICATION OF REMNANTS**

Standard interpretation of standard theory, i.e., General Relativity (GR), leads us to expect only black holes or neutron stars. We here consider in addition possibilities suggested by unusual forms of matter in standard GR, by nonstandard interpretations of GR, and by alternate theories of gravity. In the spirit of the PPN approach to gravity, we wish to consider in a categorical or parametric, theory-independent, way all possible condensed remnants, not just those that have already been considered in some detail. Therefore we here consider not specific models, but classes of models, based on three generic characteristics that strongly affect the behavior, appearance, and detectability of the class of objects.

These three characteristics are the presence or absence of singularity(s), event horizon(s), and hard surface(s). Black holes and neutron stars differ on all three of these criteria. Some of the other alternatives are “intermediate,” in that they possess some of the traits of a black hole and some of the traits of a neutron star. This makes distinguishing the various possibilities even more difficult.

**CLASSIFICATION OF CONDENSED OBJECTS**

We begin with the standard possibilities. A black hole has an event horizon and a singularity, but no hard surface. Just the opposite, a neutron star has a hard surface, but no event horizon and no singularity. Among the less frequently considered alternatives, the strange, quark, boson and soliton stars all fall in the
same category as the neutron stars; in fact they could be described as smaller, denser, and perhaps harder or stiffer neutron stars. The naked singularity is in a class by itself, with no hard surface and no event horizon, but obviously a singularity. Of course, the singularity can be pointlike or ringlike; spacelike, timelike or null; and of dimensions ranging from zero to three. Many different varieties of naked singularity have been discussed. Wormholes need to be subdivided to fit into our categories. The classical wormhole [15,16], which has been described as "two black holes glued together at the event horizon," would have an event horizon, but no singularity and no hard surface; the Einstein-Rosen bridge also falls in this category. The more modern "traversable" wormhole [17], (which requires exotic matter for its construction) has no event horizon, no hard surface, and no singularity. Also in this category are the red hole or the big red bag and the eternally collapsing object. The frozen star [11] concept, which was an earlier understanding of the Schwarzschild solution that has now been largely replaced by the black hole paradigm, did seemingly have a hard surface, as well as what we now call an event horizon, and the singularity was hidden by both the event horizon and the hard surface. In this version, the frozen star had all three characteristics: a hard surface, an event horizon and a singularity. In other interpretations (see e.g. Rosen [12]), the hard surface prevented the singularity from forming, and the frozen star had only an event horizon and a hard surface without a singularity.

**OBSERVATIONAL EFFECTS OF SELECTED CHARACTERISTICS**

A hard surface can absorb or reflect infalling energy in the form of matter or radiation. If it does absorb the infalling energy, it heats up and reradiates at least some of the energy, perhaps at a different wavelength and perhaps slowly over time, but all the infalling energy is at least potentially observable and, in principle, recoverable. Thus accretion energetics and cooling curves can the presence or absence of a hard surface.

An event horizon is a "one-way membrane" that absorbs and hides all infalling energy. The energy is lost from the view of the external observer and can not be seen or recovered (except quantum mechanically), although its mass can be detected gravitationally. Hence energy balance calculations and observations can be a critical indicator of an event horizon.

A point singularity can be treated as a hard surface of radius zero that immediately reflects or reradiates all infalling energy. Or it can be treated as an event horizon of radius zero that absorbs without (nongravitational) trace all infalling energy in whatever form. Or it can be treated as a source of total unpredictability, leading to totally random and unpredictable results, possibly even including non-conservation of normally conserved quantities. Or it can be treated as an indication that the theory has broken down, and must be modified. Higher dimensional and more complex singularities can be treated analogously.
If the singularity is not hidden, it might be indicated by higher temperatures, faster re-radiation, and a smaller apparent size.

**DISTINGUISHING COLLAPSED REMNANTS**

It has been surprisingly difficult to detect the difference between black holes and neutron stars. So far the only ironclad technique has been the detection of highly regular pulsar radiation, which is conclusively diagnostic for the presence of a neutron star. Other observational surprises include the inability to detect any compact remnant in many non-type Ia supernovae remnants, and the difficulty of conclusively detecting pulsars whose beam is not directed at us. Detecting intermediate objects whose properties are less well understood can only be substantially more difficult. Nevertheless, there have been observations that are hard to interpret with standard neutron star and black hole models, which have led to the suggestion that perhaps one of these less familiar candidates is being observed.

Possible means of observing or constraining the condensed remnant include: direct and indirect observation of size and shape, collapse energetics, early and late cooling curves, and chemical composition of SNR ejecta.

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