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Multimessenger Astronomy in Practice

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Chapter 1

Multimessenger Astronomy in Practice: Celestial Sources in Action

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1.1 Introduction

Although the first nonelectromagnetic messengers from space—cosmic rays—were discovered in the early 20th century,[1] it is only now that multimessenger astronomy is coming into its own. Neutrino and gravitational-wave detections are being combined with cosmic-ray and electromagnetic messengers to illuminate our view of the cosmos, especially parts with high energy density and fast variation. Gravitational-wave detections of energetic mergers and their aftermaths involving neutron stars and stellar-mass black holes are opening doors of understanding to events including gamma-ray bursts (GRBs), fast radio bursts (FRBs), and high-energy neutrino detection. Supernovae (and their remnants), pulsars, magnetars, and active galactic nuclei (AGNs) are natural particle accelerators that can be used to analyze very high-energy processes.

As discussed in the companion volume to this book (*Principles of Multimessenger Astronomy*, hereafter "Book 1"), the invention of the telescope and its subsequent refinement and use by Galileo marked the birth of the modern scientific method, setting the stage for a dramatic reassessment of our place in the cosmos. This technological breakthrough demonstrated that there is much more to the universe than is available to our unaided senses. These revelations, in time, have established the unforeseen vastness of our dynamic, expanding universe; shown that our Galaxy is but one among countless others; and introduced us to a wealth of exotic astrophysical structures. There are now telescopes to cover the entire multimessenger spectrum, located on Earth, in the sky and in space.

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[1] Meteorites could be regarded as messengers, but are out of our scope.

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Galileo's *Letters on Sunspots*[2] can also be thought of as a foundation of time-domain astronomy—the study of how astronomical objects change with time, which is a fundamental aspect of today's multimessenger astronomy. Gravitational waves, for example, arise from changes in physical structure. Advanced Laser Interferometer Gravitational Wave Observatory (LIGO) detected the first gravitational wave (GW 150914) in 2015—even before the final test run was complete. Since then, several binary black hole (BBH) mergers as well as at least one binary neutron star coalescence have been discovered (see Book 1, Chapter 8, and Chapters 9 and 10 of this work).

1.1.1 Observational Breakthroughs

New and intriguing observations have been performed at scales from compact stellar-mass objects to galaxy clusters. The fact that most of these observations can be classified into a rough size scale is itself an achievement of multimessenger observations.

Stellar Scale:

- The binary neutron star merger GW 170817, detected in gravitational waves and as a GRB (Chapter 9);
- TeV gamma-ray observations of several GRBs, probing prompt and afterglow phases (Chapter 7);
- The F-type star KIC 8462852 (a.k.a. Boyajian's star) at a distance of only 450 pc, hypothesized to have a swarm of artificial objects in order to explain its peculiar light curve (Chapter 11);
- The ultraviolet (UV) spectra of the hot star ξ Per (Chapter 5);
- Detection of FRB 200428 in the same direction as the magnetar SGR 1935 +2154 (Section 1.2.5).

Galactic Scale:

- The revelation of giant gamma-ray structures—the Fermi bubbles—emanating from the center of the Milky Way Galaxy, extending ~7700 pc (north and south) of the Galactic Plane (Chapter 7);
- The detection of neutrino emission from the blazar TXS 0506+056 (Chapter 8); IceCube's detection of "astrophysical" neutrinos is a benchmark discovery with great implications, prompting questions such as where are the neutrinos produced—in the interstellar medium (ISM), in the intergalactic medium, or as a superposition of individual sources, starburst galaxies, AGN, etc.?
- Discovery of the first low-frequency radio counterpart to an unidentified TeV gamma-ray source (Chapters 2 and 7);
- Discovery of mysterious odd radio circles (ORCs) (Chapter 12).

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[2] *Istoria e Dimostrazioni intorno alle Macchie Solari.*

Cluster Scale:

- Unequivocal evidence for the extragalactic origin of the highest-energy cosmic rays (Chapter 7);
- The Bullet Cluster (1E 0657–56) and dark matter (Chapter 10).

1.1.2 New Instruments

A new generation of detection instruments, together with upgrades to existing ones, are being designed and are coming online at a rapid pace, including both ground and space-based detectors.

The US-based Cosmic Explorer will be similar to the LIGO detector but with 40 km arms. The Einstein telescope will have three 10 km long arms in a triangular configuration and will be located partially underground. These detectors have a minimum frequency limited to 5 Hz. Space-based observatories will probe much lower frequencies to detect massive black hole binaries and gravitational-wave backgrounds. They include LISA, TianQin, and DECIGO. In addition to laser interferometers, pulsar timing arrays (PTAs) are being designed for gravitational-wave detection of frequencies down to nanohertz (Kembhavi & Khare 2020).

Telescopes based on the detection of Čerenkov radiation (see Book 1, Chapter 7, and Chapter 7 of this work) can detect high-energy messengers such as cosmic rays, gamma rays, and neutrinos using the particles they create, such as muons. These detectors are found on the ground, underground, and deep in oceans. Example instruments include the Cherenkov Telescope Array (CTA) for TeV gamma-ray detection and IceCube, the Cubic KiloMetre (km3) Neutrino Telescope (KM3NeT), and the Pierre Auger Observatory for neutrino and cosmic-ray detection (see Book 1, Chapter 7 and Chapter 8).

An essential complement to these new instruments is the coordinating organization that allows the information from one detector to be disseminated quickly to the others, which can then search for counterparts. This is vital to the transition from multiwavelength to multimessenger astronomy.

1.1.3 Theoretical Synergies

In order to create a realistic picture of the universe, theoretical research is essential to understand multimessenger astrophysics in a consistent and coherent way. The most crucial requirements to enable theoretical contributions are free access to data and open communication. Computational requirements range from minimal to high-performance computing facilities (Chapter 12).

Example applications of theoretical studies in high-energy multimessenger astrophysics include:

- Understanding the astrophysical processes that lead to the generation of electromagnetic radiation, neutrinos, and cosmic rays. Such processes include cosmic-ray/proton collisions, inverse-Compton scattering, bremsstrahlung, matter/antimatter production and annihilation, photopion production, curvature radiation, synchrotron radiation, and radioactive decay (see Book 1); they arise in supernova remnants (SNRs), pulsar environments, accreting objects (AGNs, X-ray binaries, microquasars), starburst galaxies, cataclysmic events (supernovae, hypernovae, kilonovae, compact mergers), massive stellar winds and clusters, and ISM clouds.

- Jet simulations from X-ray to radio data, allowing us to understand the ejecta from GW 170817, probe microquasar physics, and simulate blazar neutrino production.
- Simulations of Galactic cosmic-ray and electron propagation using magnetic fields, infrared (IR) photon, and ISM gas distributions, reproducing the cosmic-ray flux at Earth, diffuse GeV gamma-ray emission, and diffuse Galactic neutrino fluxes. Such simulations[3] can be used to provide improved predictions of the diffuse TeV gamma-ray emission that is expected to be detected by the CTA.
- Prediction of TeV gamma-ray morphology from the propagation of cosmic rays and electrons into ISM clouds, predicting the emission seen by HESS (High Energy Stereoscopic System) and to be explored more deeply by CTA.
- Central Milky Way outflow modeling from accretion or stellar winds.
- Simulations of low-mass galaxies, in which cosmic-ray pressure may open magnetic field lines, allowing gas escape that stops star formation.
- High-energy gamma-ray and neutrino observations to understand the dark matter that dominates the formation of cosmic structure, the first stars, and galaxies.
- Using gamma-ray observations from GW 170817 and AGN flares to place strong limits on Lorentz invariance violations.

1.2 The Multimessenger Event Zoo

The story of multimessenger astronomy so far is one of particular sources and classes of sources (Figure 1.1), for which multimessenger observations yield unique insights into their nature. Ultimately, however, the goal is to understand the astrophysical processes that lead to the emission of each messenger and that affect the messengers as they traverse intergalactic and interstellar space to reach us (Figure 1.2). More details of specific sources or events can be found throughout various chapters of this book.

1.2.1 Gamma-Ray Bursts

GRBs are a diverse group of energetic explosions lasting from milliseconds to hours and associated with “afterglows” at wavelengths longer than gamma rays (Figure 1.1; also see Chapter 7). These transient gamma-ray events were first discovered in the 1960s by the Vela satellites.[4] For decades, all that was known about GRBs was their gamma-ray emission, that they were isotropically distributed over the sky, that they did not repeat, and that they were clearly extraterrestrial.

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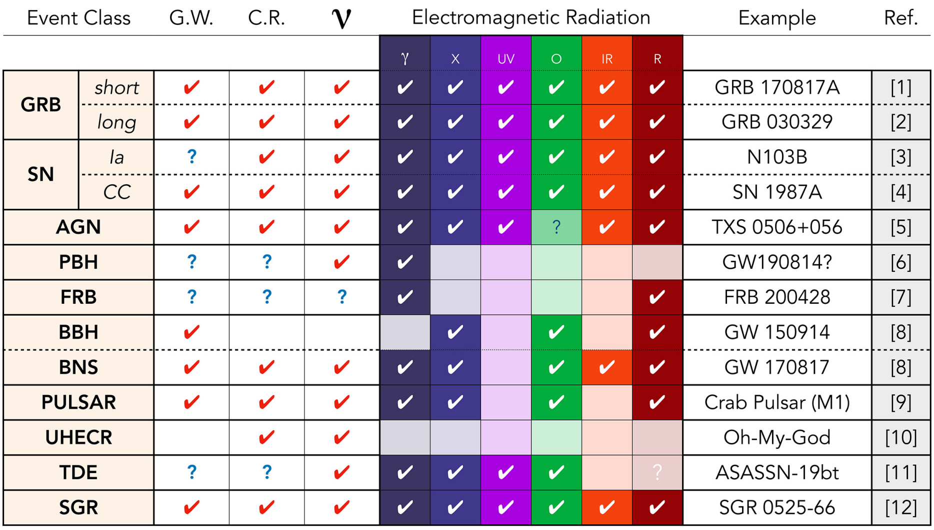
[3] Run with the GALPROP code, at the time of writing.

[4] Designed to verify treaties that banned atmospheric nuclear detonations, they detected no illicit nuclear tests—except possibly in 1979.



Event Class		G.W.	C.R.	ν	Electromagnetic Radiation						Example	Ref.
					γ	X	UV	O	IR	R		
GRB	*short*	✔	✔	✔	✔	✔	✔	✔	✔	✔	GRB 170817A	[1]
	long	✔	✔	✔	✔	✔	✔	✔	✔	✔	GRB 030329	[2]
SN	*Ia*	?	✔	✔	✔	✔	✔	✔	✔	✔	N103B	[3]
	CC	✔	✔	✔	✔	✔	✔	✔	✔	✔	SN 1987A	[4]
AGN		✔	✔	✔	✔	✔	✔	?	✔	✔	TXS 0506+056	[5]
PBH		?	?	✔	✔						GW190814?	[6]
FRB		?	?	?	✔					✔	FRB 200428	[7]
BBH		✔				✔		✔		✔	GW 150914	[8]
BNS		✔	✔	✔	✔	✔		✔	✔	✔	GW 170817	[8]
PULSAR		✔	✔	✔	✔	✔		✔		✔	Crab Pulsar (M1)	[9]
UHECR			✔	✔							Oh-My-God	[10]
TDE		?	?	✔	✔	✔	✔	✔		?	ASASSN-19bt	[11]
SGR		✔	✔	✔	✔	✔	✔	✔	✔	✔	SGR 0525-66	[12]

Figure 1.1. Examples of multimessenger events. Abbreviations: G.W.—gravitational waves, C.R.—cosmic rays, ν—neutrinos, γ—gamma rays, X—X-rays, O—optical, R—radio, IR—infrared, UV—ultraviolet, GRB—gamma-ray burst, SN—supernova, CC—core collapse, AGN—active galactic nucleus, PBH—primordial black hole, FRB—fast radio burst, BBH—binary black holes, BNS—binary neutron stars, UHECR—ultra-high-energy cosmic rays, TDE—tidal disruptive event, and SGR—soft gamma repeaters. References: [1] Abbott et al. (2017); [2] Stanek et al. (2003); [3] Li et al. (2017); [4] Fryer et al. (2019); [5] Britzen et al. (2019); [6] Scholtz & Unwin (2020); [7] Zhang (2020); [8] Kembhavi & Khare (2020); [9] Hewish et al. (1968); [10] Anchordoqui (2019); [11] Holoien et al. (2019); [12] Moskvitch (2020).

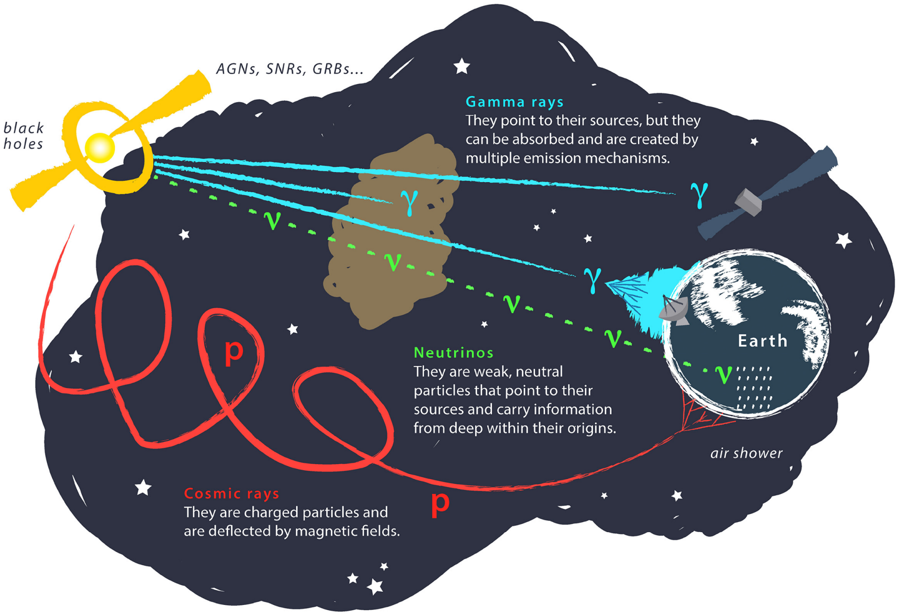


Figure 1.2. High-energy sources emit multiple messengers, including gamma rays, neutrinos, and cosmic rays. Cosmic rays are deflected by magnetic fields, making it hard to trace their origin at lower energies. Image credit: IceCube Collaboration/WIPAC, Juan Antonio Aguilar, and Jamie Yang.

The debate over the nature of GRBs was intense and ongoing. Over 30 models for their origin had been proposed by the end of the 1970s,[5] generally falling into three classes: accretion, stellar activity, and stellar destruction. Some of these models had GRBs as nearby Galactic phenomena, while some models placed them at cosmological distances, requiring very high luminosity.

In order to understand GRBs, it was necessary to observe more than just the gamma rays. The key to unraveling the mystery was a combination of specialist monitoring instruments to spot new GRBs and organization to observe them as soon as they were detected—all within the minutes-to-hours timeframe. The BATSE[6] instrument on the Compton Gamma Ray Observatory satellite[7] detected about one GRB per day over the course of its 9 year mission, at sub-MeV energies. The rapid response required for facilities at other wavelengths drove significant development in telescope automation, operation and scheduling software, and human organization.[8] Detection and follow-up were brought together by the Swift satellite,[9] which combines a wide-field gamma-ray telescope to detect the bursts with x-ray and UV/optical telescopes to observe the burst position.

These coordinated observing campaigns showed that the afterglows of GRBs were to be found in distant galaxies with redshifts of one or more, settling the GRB debate in favor of cosmological models. With reasonably well-known distances, the energy release of a GRB can be estimated; that of a long burst ranges from 10^{52} to 10^{54} erg.[10] Energies of this magnitude are equivalent to the conversion of about a solar mass into energy, with an efficiency of about 10%. The difficulty of explaining such a high energy leads to models that invoke geometric beaming to boost the brightness of the burst.

The basic gamma-ray emission mechanism for GRBs is thought to be an inverse-Compton scattering, where preexisting lower-energy photons are scattered by relativistic electrons within an explosion, gaining energy from the scattering event and becoming gamma rays. The longer-wavelength afterglow emission is thought to be the result of the explosion moving outward at close to the speed of light, colliding with surrounding interstellar gas and creating a shock wave, with a possible reverse shock propagating back into the ejecta.

For an excellent "historical primer" about GRBs, the reader is directed to Andrew Levan's "Gamma-Ray Bursts" publication (Levan 2018).

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[5] And up to 118 models by the early 1990s.

[6] Burst and Transient Source Experiment.

[7] CGRO, one of NASA's Great Observatories, operated in 1991–2000.

[8] Astronomers already had systems in place to handle these problems in the hours-to-days timeframe—the Central Bureau for Astronomical Telegrams was founded in the 19th century. The challenge was to set up systems for follow-up observations in minutes. The *Hotwiring the Transient Universe* conference series brought many of these elements together.

[9] The Neil Gehrels Swift Observatory, a NASA medium-class Explorer satellite, launched in 2004, still operational at the time of writing.

[10] The most commonly used energy unit in astronomy, equivalent to 10^{-7} J; shorter bursts (under about 2 s) are less energetic by approximately two orders of magnitude.

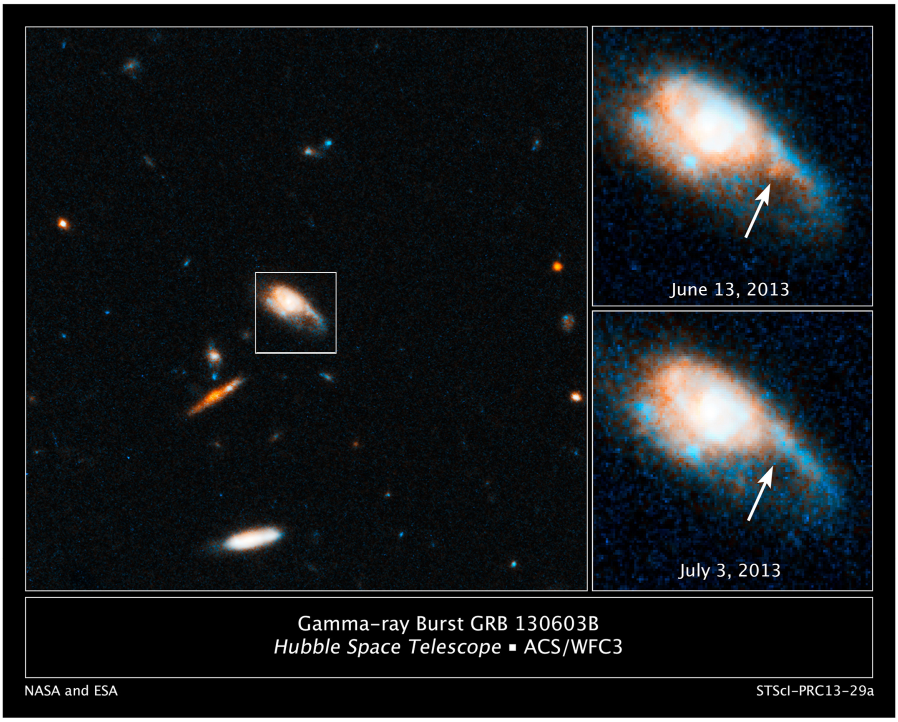

Figure 1.3. Kilonova or glow created during the short GRB 130603B event as seen by the HST. The glow was clearly seen on 2013 June 13 but had faded when observed on 2013 July 3. Image credit: National Aeronautics and Space Administration (NASA), European Space Agency (ESA), N. Tanvir (University of Leicester), A. Fruchter (STSci), and A. Levan (University of Warwick).

1.2.1.1 Short GRBs

Short-duration GRBs are events with a duration less than 2 s and account for 30% of all GRBs. The nature of these events was initially unknown but one clue was their short mean duration of 0.2 s, suggesting the physical diameter of their progenitors was less than 0.2 light-second (about four times Earth's diameter).

These events are most likely associated with binary mergers, specifically, a neutron star merging with another neutron star or black hole. This produces a kilonova[11] (Figure 1.3). This identification of the origin of short GRBs with kilonovae (Section 4.4.1) has become more secure with the detection of GRB 170817A associated with gravitational wave GW 170817 that signaled the merger of two neutron stars (Abbott et al. 2017).

1.2.1.2 Long GRBs

Long GRBs (duration >2 s) comprise the majority of events, last longer, and have the brightest afterglows, so they have been studied more extensively. Most long events are associated with star-forming galaxies, and specifically with core-collapse

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[11] Although a small number may be produced by giant flares from soft gamma repeaters in nearby galaxies.

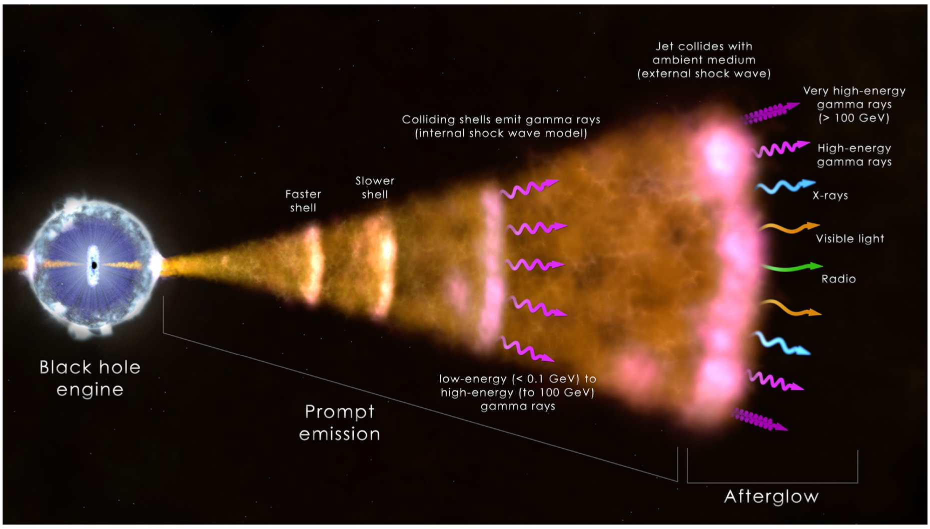

Figure 1.4. General picture of the shocks and related particle acceleration regions within a GRB jet originating from either a core-collapse supernova (LGRB) or a compact object merger (SGRB). The prompt and afterglow regions are also defined. Image credit: NASA/Goddard Space Flight Center/ICRAR.

supernovae (CCSNe; Woosley & Bloom 2006). This identification arose from sources such as GRB 030329, the first burst whose afterglow showed the characteristics of a supernova (Stanek et al. 2003). As with any supernova event, high-energy neutrinos may also be produced in these explosions. These neutrinos would be in the TeV range, distinguishable from lower-energy (MeV) neutrinos from supernovae or the Sun; however, they are yet to be found. The production of cosmic rays is also likely to arise, due to the acceleration of charged particles by supernova shocks (Figure 1.4). These protons and heavier nuclei could be accelerated to relativistic velocities, possibly yielding ultra-high-energy cosmic rays.

A few GRB events have lasted more than 10^4 s and have been proposed as a separate class (ultralong gamma-ray bursts). Proposed progenitors include the collapse of a blue supergiant (Gendre et al. 2013), a tidal disruption (Greiner & Mazzali 2015), or a newborn magnetar[12] (Greiner & Mazzali 2015).

1.2.2 Supernovae

Supernova (SN) events can be divided into two major categories: Type Ia events, in which a white dwarf star undergoes thermonuclear detonation and core-collapse events, in which the core of a high-mass star undergoes gravitational collapse after exhausting its supplies of fuel for nuclear fusion. Both types of explosion drive matter out into the interstellar medium around the star, and the latter type leaves a compact object remnant (a neutron star or a black hole). Understanding the physics

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[12] A type of neutron star with an extremely powerful magnetic field, 10^{13}–10^{15} G, 10^9–10^{11} T.

of these events requires extensive use of data from all available messengers (see Chapters 2, 3, 4, 5, 6, 7, and 8).

1.2.2.1 Type Ia Detonation

Type Ia SNe are thought to be thermonuclear detonations of carbon–oxygen white dwarfs (WDs). Although the events leading up to the detonation are not perfectly understood, the outline is fairly clear: These stars cannot have mass $>1.44\ M_\odot$ (the Chandrasekhar limit), but if they are in binary systems they will gradually accrete mass until they reach the limit. As they reach the limit, the carbon and oxygen undergo runaway nuclear fusion, which drives the explosion. The nature of the progenitor is often unclear: WD–WD binary systems can give rise to a double-degenerate supernova, while systems made up of a WD and a main-sequence or giant star generate single-degenerate supernovae. Examples of a Type Ia SN in which the nature of the progenitor system is yet to be confirmed are J0509–66731 and N 103B located in the Large Magellanic Cloud (LMC; Bozzetto et al. 2014; Li et al. 2017; Roper et al. 2018, Sano et al. 2018; Alsaberi et al. 2019). However, a single-degenerate scenario is preferred for SNR N103B but double degenerate for SNR J0509-6731. Double-degenerate supernovae from binary WDs would produce gravitational-wave signals from the inspiral, leading to the merger and explosion (in addition to electromagnetic, neutrino, and cosmic-ray messengers), so space-based gravitational-wave detectors sensitive in the decihertz range such as DECIGO could observe such WD–WD mergers directly (Kinugawa et al. 2019).

Neutrinos detected from CCSNe can reveal important information about the dynamics of the explosion, and neutrinos from thermonuclear SNe also have similar potential. Type Ia SNe are dimmer neutrino sources, but detectors such as Hyper-K may be able to detect their neutrinos out to 10 kpc. For a relatively near Type Ia SN at 1 kpc, JUNO, Super-K, and DUNE could find a few events, while IceCube, KM3NeT, and Hyper-K could find several tens of events (Wright et al. 2016; Aiello et al. 2019; Aiello & Albert 2021).

1.2.2.2 Core Collapse

Multimessenger observations of CCSNe could be considered to date back a half-century to the study of dust grains that probed the products of a CCSN, but for our purposes, multimessenger observations of CCSNe started with the concurrent neutrino and electromagnetic observations of SN 1987A in the LMC (Figure 1.5). Most of the energy output of a CCSN is carried by MeV neutrinos, and these should be detectable out to a few tens of kiloparsecs by next-generation detectors (Fryer et al. 2019; Aiello & Albert 2021), such as Super-Kamiokande, DUNE, JUNO, KM3NeT, and IceCube. Because the neutrino pulse is generated by the nuclear reactions in the core of the star, it can be used in conjunction with detailed modeling to probe the physics of supernova explosions. In addition, observation of the diffuse neutrino background has the potential to place limits on populations of CCSNe.

Observations of electromagnetic emission span the progenitor star, the explosion itself, and the remnants. If the star that underwent the supernova was already known, cataloged, and hopefully even classified spectroscopically, the supernova

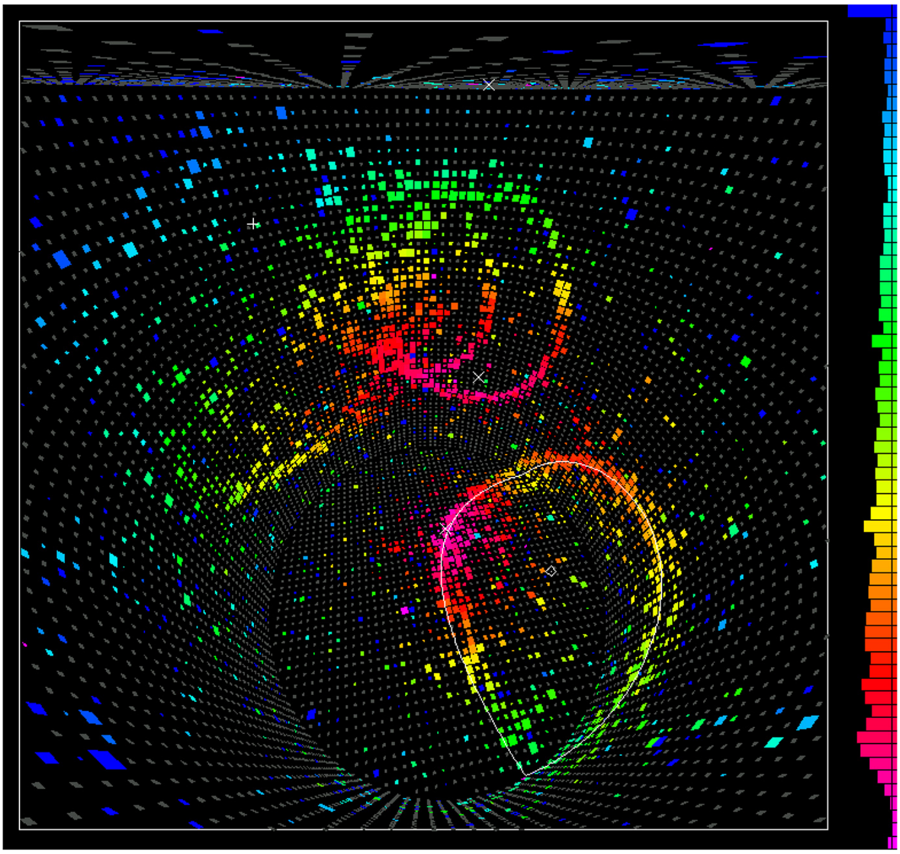

Figure 1.5. Multiple neutrino events, reconstructed from separate neutrino detectors. In 1987, three independent detectors that were sensitive to energetic neutrinos and antineutrinos detected a total of 25 particles in a single burst spanning 13 s. A few hours later, the light arrived as well. Image credit: Super-Kamiokande Collaboration/Tomasz Barszczak.

will deliver far more astrophysical insight, as was the case for SN 1987A. In the early stages of the explosion, the electromagnetic radiation is trapped until shock breakout, accompanied by a burst of UV and X-ray photons. The modern fleet of transient-focused facilities (particularly Swift) have made it possible to observe shock breakout, as they can get to a supernova in time to see it.

The nucleosynthesis that occurs in CCSN is an inherently multimessenger phenomenon (Fryer et al. 2019), producing the neutrino pulse and delivering new elements into the remnant. Electromagnetic observations can then probe the nucleosynthetic yields of the explosion, via IR, optical, and UV spectra (especially in the nebular phase) and in gamma-ray decay lines.

The shocks that CCSN drive into their surrounding medium are engines for cosmic-ray generation, making cosmic rays a probe of the aftermath of the supernova, while gravitational waves are expected to deliver information from the "engine" of the supernova explosion. In particular, strong gravitational-wave signals should arise from rapidly rotating stars, probing stellar rotation, asymmetry, and the convective engine. CCSNe may be able to produce gravitational waves detectable with advanced LIGO to 10 Mpc.

Distance is the key limitation to what we can learn about CCSNe. Detailed analysis is often limited to Galactic objects (Hurley-Walker et al. 2019a, 2019b) or at best the nearby Magellanic Clouds (Maggi et al. 2016, 2019; Bozzetto et al. 2017), while most SNe happen farther out in the universe. Validation of our models with nearby events, however, may eventually allow us to use the array of messengers to study more distant CCSNe, even back to the early universe.

1.2.3 Active Galaxies

The centers of most (and maybe all) large galaxies contain a supermassive black hole (SMBH) with mass of order $10^8\ M_\odot$. These black holes accrete interstellar gas episodically, and during accretion are observed as AGNs. The accretion process releases vast amounts of electromagnetic radiation, and some of the matter from the accretion disk is ejected perpendicular to the disk as bipolar plasma jets at relativistic speeds which in turn drive high-speed gas outflows.

The initial signatures of AGN emission were found in the first half of the 20th century; radio astronomy was a major catalyst to understanding them (for example see Figure 1.6). The process of understanding them has been long, not only because they are often very distant, but because they seem to have a complex structure consisting of an SMBH surrounded by an accretion disk, a complex torus of material around the disk, and bipolar jets. The high magnetic fields of these jets and

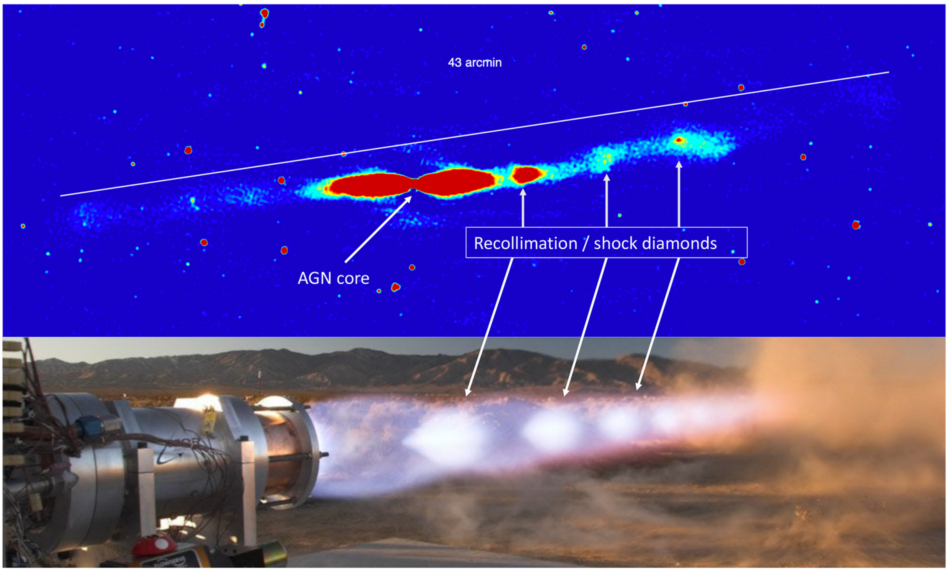

Figure 1.6. (Top) Australian Square Kilometre Array Pathfinder (ASKAP) 1.5 GHz image of the AGN NGC 2663, showing recollimation knots in the southern jet. (Bottom) “Shock diamonds” in jet engine exhaust, resembling the recollimation knots in NGC 2663, but on a much smaller scale. Image credit: (top) V. Velović and M. D. Filipović; (bottom) Mike Massee/XCOR.

the shocks that are found in them are efficient particle accelerators and the best candidates for the production of cosmic rays beyond the “knee” (10^{15} eV)—particularly quasar jets (Chapter 8).

AGNs can be divided into radio-quiet and radio-loud objects—the latter due to synchrotron emission from both the jets and the radio lobes of plasma that the jets inflate. They can also have radically different appearances, depending on the direction from which they are viewed (Figure 1.7). Based on characteristics like activity, emission lines (narrow or broad), variability, jets, and the presence of X-ray, UV, and far-IR radiation, AGNs have been classified as normal, LINER (low-ionization nuclear emission-line region), Seyfert I, Seyfert II, quasar, blazar, BL Lacertae, OVV (optically violent variables), radio galaxies, and more. Although these classifications are still used, it is accepted that they refer to similar objects—an idea known as unification.

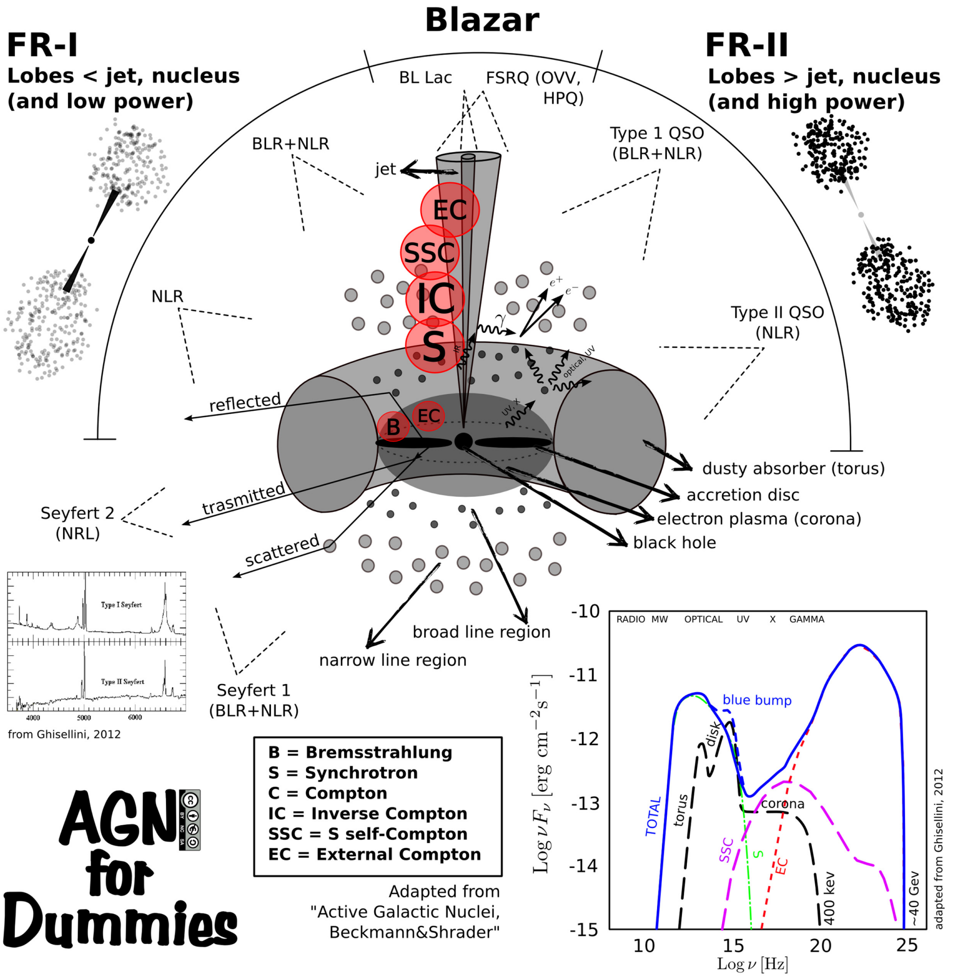

Figure 1.7. The unified AGN Model. Image credit: Brunetto M. Ziosi (http://brunettoziosi.com/posts/agn-for-dummies/).

Blazars, for example, are AGNs viewed from a position illuminated by the cone of a relativistic jet. Within this jet, particles are accelerated by Fermi shocks in matter blobs traveling with a Lorentz factor (γ) of 10 or higher. This environment allows the production of high-energy particles including pions and neutrinos (Zuber 2020), making blazars potential neutrino sources. The neutrino event IceCube 170922A detected at the South Pole was reported to originate from TXS 0506 +056, of BL Lac type, at a distance of order a gigaparsec ($z = 0.34$) from Earth (Chapter 8) with a suspected precessing jet–jet interaction (Britzen et al. 2019).

Quasars, the most energetic AGNs, are triggered during mergers of gas-rich spiral galaxies. These mergers not only trigger massive star formation but also result in SMBH binaries at the center of the newly merged galaxy. When SMBH binaries coalesce, enormous outbursts of gravitational waves and electromagnetic radiation are expected, including radio, microwave, IR, optical, UV, X-ray, and gamma-ray wavebands. Gravitational-wave-producing inspirals could also be produced by the formation in the AGN region of massive stars that would collapse into compact objects and merge into the central SMBH. A population of these could contribute to the gravitational-wave background detectable by LISA above a few millihertz at a rate of 10–100 per year (Schnittman et al. 2006).

Our own Milky Way Galaxy—which contains a central SMBH—has probably undergone AGN episodes in the past, leaving the Fermi Bubbles (Figure 1.8) as relics of bipolar outflow (see Section 7.5.5).

1.2.4 Primordial Black Holes

PBHs are a hypothetical population of black holes formed by the gravitational collapse of overdense regions of space when the universe was less than a second old. They were proposed by Zeldovich[13] and Novikov[14] in the mid-1960s, and studied in depth by Hawking.[15] Because PBHs arise from dense regions rather than stars, they do not have the same mass limitations as stellar black holes; there is no known stellar evolutionary pathway that can deliver a black hole with mass less than a few solar masses—but PBHs can have masses as little as 10^{-8} kg. The idea has even been entertained that the proposed Planet 9 could be a PBH with mass several times that of Earth (Figure 1.9), but which is almost undetectable (Scholtz & Unwin 2020).

As gravitational-wave detectors start to find more black holes in binary systems, more candidates are found whose masses are inconsistent with stellar evolutionary theory, and these may be relic PBHs from the early universe, which have grown by accretion and/or merger. The 2.5–2.7 $M_\odot$ component of GW 190814 is an example (Clesse and Garcia-Bellido 2020; and see Chapter 9), as are the gravitational-wave-detected black holes of a few tens of solar masses. Attributing these binary merger components to PBHs, however, requires fine-tuning the amount of time that elapses between formation and merger of such objects to explain the merger rate (Vattis et al. 2020).

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[13] Yakov Borisovich Zeldovich (1914–1987), Russian astrophysicist.

[14] Igor Dmitriyevich Novikov (1935–), Russian astrophysicist.

[15] Stephen Hawking (1942–2018), British theoretical physicist and cosmologist.

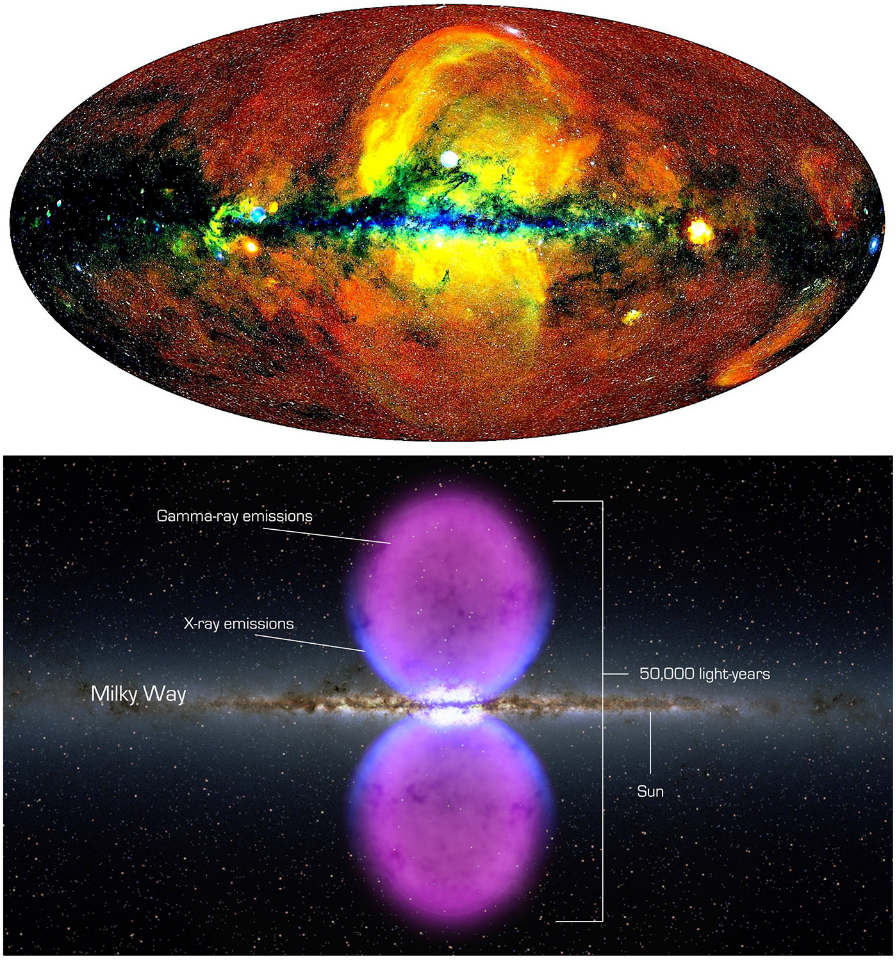

Figure 1.8. Upper: the SRG/eROSITA all-sky map of the Milky Way as a false-color image, with energies from 6 $\times 10^6$ K (red) to 15 $\times$ 10^6 K (blue). Bottom: artist impression of large-scale Fermi bubbles in the Milky Way halo. Credit: Wikipedia: JohannesBuchner (CC BY-SA 4.0)/Predehl et al. (2020) and NASA (NASA's Goddard Space Flight Center).

PBHs could also be part of the population of massive compact halo objects (MACHOs) and thus nonbaryonic dark matter candidates. However, the PBH contribution to dark matter (as well as ultra-high-energy cosmic rays) has been constrained by several observations. PBHs would be expected to generate observable phenomena, including lensing of GRBs, capture by neutron stars with rapid star destruction, capture with rapid detonation by white dwarfs, stellar microlensing, Type Ia SN microlensing, and temperature anisotropies of the CMB. Further constraints on the PBH population may come from the next-generation Square Kilometre Array (SKA) radio telescopes probing the effects on the reionization history of the universe due to energy injection into the intergalactic medium by accretion of matter onto PBHs.

The search for PBH encompasses many different messengers and techniques. Because PBHs can take on very low masses, they may be able to evaporate on

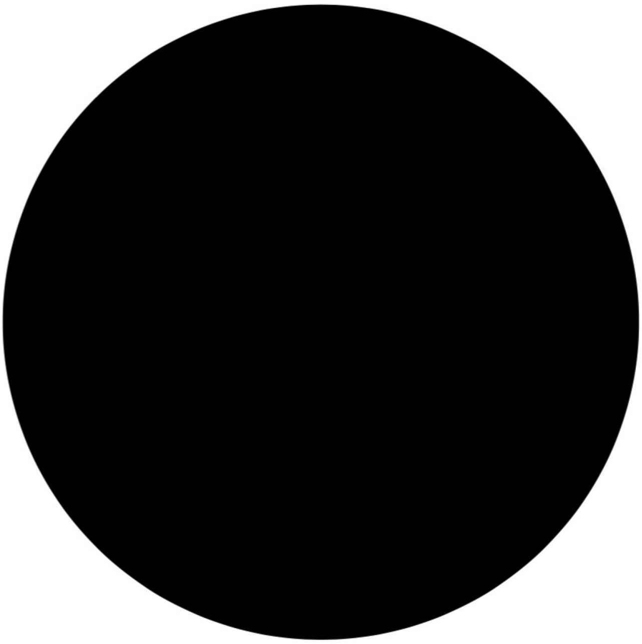

Figure 1.9. Exact scale (1:1) illustration of a 5 Earth-mass primordial black hole. Is this the mysterious Planet 9? Image credit: Reprinted with permission from Scholtz & Unwin (2020). Copyright 2020 by the American Physical Society. (CC BY 4.0).

timescales similar to the life of the universe, in which case we might expect to be able to observe the burst of gamma-ray Hawking radiation and high-energy neutrinos that are produced. The next generation of gamma-ray telescopes such as CTA will search for evaporating PBHs during their last second to year of existence, with bursts detectable out to distances of 10^{-3} to 0.1 pc. At the same time, the upgraded KM3NeT and IceCube will also be able to detect the expected neutrino emission from PBH. Gravitational-wave detectors such as LIGO could discover PBHs by mass reconstruction, finding low-mass black holes, and it may also be possible to measure large orbital eccentricities produced by PBH binaries. PTAs and LISA may find a stochastic background of gravitational waves from PBH binaries.

Observable influences of PBHs may come from observations of faint dwarf galaxy central star clusters and even positions and velocities of stars within the Milky Way. Small PBHs may pass unharmed through Earth producing acoustic signals or leave a seismic signature when passing through a star. Monitoring for microlensing of quasars by PBHs may also be possible.

1.2.5 Fast Radio Bursts

FRBs are radio pulses lasting a fraction to a few milliseconds, some of which, repeating FRBs, recur on a regular basis. Although the signals are broad band, they are often detected at frequencies around a gigahertz. The first detected FRB was found in archival data from the Parkes telescope in 2007 by Duncan Lorimer—so this initial detection is often called the Lorimer burst.

Searching for more FRBs so as to find a population has proven to be hard. FRBs can occur anywhere on the sky at any time, so finding them requires continuous monitoring of a large area of sky. The Parkes telescope, with a multiplexed receiver, was an initial leader in the field, and the ASKAP telescope, with its wide-field phased array feeds, has also found FRBs. Most FRBs are currently being discovered by more specialized instruments such as UTMOST in Australia and CHIME in Canada.

Based purely on the radio pulses, not much can be inferred about FRBs. The dispersion in their signals and their isotropic distribution on the sky are consistent with an extragalactic origin. The short duration of the pulses suggests that they arise in a compact region, and the observed polarization may constrain our models. But in order to make much more progress, it is necessary to localize them—that is, to estimate their position on the sky sufficiently accurately to allow comparison with maps from other wavebands and messengers. Wide-field radio observations generally have quite poor instantaneous angular resolution, and so it is not easy to generate a precise location for the signal. Technical developments at ASKAP allowed the first localization of a nonrepeating FRB (Bannister et al. 2019) to a position outside the center of a distant galaxy (redshift 0.3). These developments, along with those at UTMOST, should lead to greater rates of localized detection.

Repeating FRBs are much easier to localize, as the localization need not be instantaneous—however, there are only very few known repeating FRBs. The first known repeating FRB, FRB 121102, was not localized until 2017 (Chatterjee et al. 2017) and found to be associated with a star-forming dwarf galaxy (Tendulkar et al. 2017), whereas the second to be localized, FRB 180916.J0158+65, was found outside the center of a massive spiral galaxy (Marcote et al. 2020), and the two environments have little in common. With more repeating FRBs being found, this part of the puzzle may soon be solved.

There is no consensus as to the origin of these bursts, but explanations range from the collision of black holes or neutron stars to extraterrestrials. Current candidates could include any high-energy phenomenon. For example, one hypothesis is that they originate from flares emanating from magnetars (Figure 1.10): the magnetar SGR 1935+2154 is responsible for the repeating FRB 200428 (Kirsten et al. 2021),

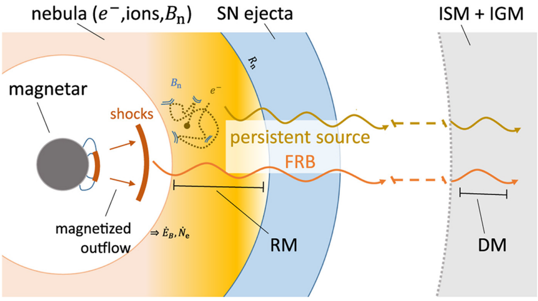

Figure 1.10. A hypothetical emission model for FRBs arising from a magnetar (highly magnetized neutron star). Image credit: Margalit & Metzger (2018).

and localizations to noncentral regions of galaxies would be consistent with this idea. Other possible FRB progenitors include young pulsars, black-hole-related outbursts, blitzars (pulsars that can rapidly collapse into black holes), black hole evaporation, stellar-mass black hole coalescence, or superradiance from PBHs (Burke-Spolaor 2018). It is not even known whether repeating and nonrepeating FRBs are the same kind of source, though current opinion is leaning toward the idea that all FRBs repeat in some way, though possibly with varying brightness and period.

Electromagnetic messengers are the only ones detected from FRBs so far, but the likelihood that they come from a region of very high energy density (implied by the short pulse duration and high power) suggests that multimessenger observations may play a role in our understanding of the phenomenon (Burke-Spolaor 2018). Neutrino detection from these events could tell us about energetic atomic decay processes and hadronic accelerations while gravitational waves can tell us about the relativistic or explosive motion of mass charge.

1.2.6 Binary Events

The merging of the components of a binary system generates gravitational waves in the frequency band most easily detected by current instrumentation, and so these events are at the forefront of gravitational-wave research. They can emerge from many different types of binary systems: black hole–black hole, neutron star–neutron star, neutron star–black hole, WD–neutron star, giant star–neutron star, and so forth. This variety of progenitors allows our detections of these events to advance our understanding of many different fields: the origin of GRBs, the physics of black holes, the origin of heavy elements, the composition of neutron star cores, and the neutron star equation of state.

1.2.6.1 Binary Black Holes

Binary black holes are a preeminent example of a phenomenon known chiefly from a nonelectromagnetic messenger—gravitational waves. Most of what we know about these systems come from the analysis of the gravitational waves emitted when they merge. This analysis is carried out by building numerical models of the system using the general theory of relativity, but simple “back of the envelope” arguments can give some insight (for fuller details, see Chapter 9 and Kembhavi & Khare 2020).

On 2015 September 14, at 09:50:45 UTC, the advanced LIGO detectors (at Hanford, WA and Livingston, LA) recorded an event lasting about 0.2 s, now known as GW 150914.[16] The LIGO arms went through about eight strain cycles, with increasing amplitude and frequency to give a “chirp” signal. The maximum amplitude was at a frequency of 150 Hz, after which the amplitude decreased in the “ringdown” phase. The signal is characteristic of a binary “inspiral,” with the bodies orbiting each other faster and faster until they merge at maximum amplitude.

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[16] The first direct detection of gravitational waves, this resulted in the award of the 2017 Nobel Prize in Physics to Rainer Weiss, Barry Barish, and Kip Thorne.

The frequency of gravitational waves emitted by a binary system is twice the orbital frequency, so the two components were orbiting each other 75 times a second at merger. The rate of frequency increase allows the chirp mass (Chapter 9, Equation (9.3)) of 30 $M_\odot$ to be calculated. The distance between them at merger can be estimated to be 350 km.

These basic parameters imply that the system must be a binary black hole: It cannot be a binary neutron star because neutron stars cannot exceed about 3 $M_\odot$; nor can it be a black hole–neutron star binary, because the 75 Hz orbital frequency would then imply a black hole mass of $\sim 1000 M_\odot$ with Schwarzschild radius[17] of ~3000 km—and the neutron star would have merged into the black hole before reaching the orbital separation implied by the signal.

The far more sophisticated modeling carried out with numerical relativity calculations is able to give more details: The two progenitor black holes had masses of 36 $M_\odot$ and 29 $M_\odot$; at merger, they were traveling at 60% of the speed of light; they merged into a Kerr–Newman black hole of mass 62 $M_\odot$ rotating 100 times a second. The mass deficit of 3 $M_\odot$ represents the energy released in gravitational radiation in a fraction of a second.[18] Signal modeling also gives a distance of 440 Mpc (redshift 0.093)—this distance estimate does not need electromagnetic radiation, and merger signals like this can be used to constrain cosmological models.

From the number of subsequent detections of black hole–black hole mergers, it appears that binary black holes are fairly common, which was unexpected. It is also possible that there are binary supermassive black holes. We know of no binary SMBH in the nearby universe, but an SMBH–SMBH merger at 250 Mpc would likely be detectable with multiple messengers.

1.2.6.2 Binary Neutron Stars

Several BBH mergers had already been detected by 2017 August 17, when advanced LIGO and advanced Virgo in Italy detected a 100 s signal denoted GW 170817 (Chapter 9); because all three detectors were operational, the gravitational-wave source could be localized to an area of 31 deg^2 on the sky. A GRB was also detected in the same part of the sky 1.7 s after the peak of the gravitational-wave signal, and this generated a GCN[19] alert in under a minute, using the well-established procedures established by the GRB community. The gravitational-wave data analysis proved challenging, so the gravitational-wave event was not sent out for some hours. It was the GRB that allowed telescopes to study the source within minutes of the signal arrival.

The combination of gravitational-wave data, gamma-ray burst, and multiwavelength electromagnetic follow-up shows this event to have been the merger of a neutron star–neutron star binary system (or BNS). Such a merger is very different from the BBH merger outlined above. While the BBH cannot be seen except in

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[17] Named after Karl Schwarzschild (1873–1916), German astrophysicist.

[18] Because the progenitors were black holes, we expect that very little of this energy would have been released in other messengers.

[19] Gamma-ray burst Coordinates Network.

gravitational waves just before the merger, the BNS merger results in a very bright transient phenomenon seen throughout the electromagnetic spectrum. If one of the progenitor neutron stars is a pulsar, it may even be detected long before the event.

The differences arise because the neutron stars are extended objects, so the gravitational field of each produces strong tides on the other. These tides tear the stars apart so that some of the matter is ejected from the merger. This will form a cloud or disk of ejecta, and this is the source of the electromagnetic radiation.

One part of the ejected matter is likely to be a jet, and this is thought to be the location of the short GRB. The rate of gamma-ray emission from GW 170817 was 10^4 times smaller than other such known bursts. It has been suggested that the weaker emission is due to the jet being seen at an angle. Optical and near-IR spectra of the ejecta of GW 170817 show large amounts of heavy elements created by the r-process[20] after the merger. The decay of these unstable isotopes powers a kilonova, and it is the kilonova that is observable by its electromagnetic radiation. These observations are consistent with kilonova models, including the production of large amounts of gold and platinum—BNS mergers may be the principal source of these elements in the universe.

Modeling of the gravitational waves indicates that the progenitors of GW 170817 had masses of 0.86 to 1.36 $M_\odot$ and 1.36 to 2.26 $M_\odot$, with a total combined mass between 2.73 and 2.82 $M_\odot$ before the merger.[21] The product of the merger is modeled to be a hypermassive neutron star[22] with mass $\sim 2.8 M_\odot$, larger than many estimates of the upper mass limit for a neutron star, so it is likely that it very quickly collapsed into a black hole. This would be consistent with the lack of gravitational-wave emission after the initial signal; but there are signs of such emission in later analyses, which would be consistent with the merger product being a hypermassive magnetar. Continued modeling of this event is yielding new insights into the structure, composition, and merger of neutron stars (Figure 1.11).

Gravitational-wave and electromagnetic observations agree on the location of the merger—the galaxy NGC 4993 (Figure 9.8), about 40 Mpc away (Section 9.7.1), much closer than the previously detected BBH. GW 170817 is one of the prototypical multimessenger events, in which the combination of gravitational-wave detection and electromagnetic-wave observations reveal an extraordinary breadth and depth of detail about this event. As such, it demonstrates some of the promise of multimessenger astrophysics. BNS mergers like it may go on to produce neutrino or cosmic-ray detections as well.

1.2.7 Pulsars

The idea of a neutron star—a stellar-mass object composed almost entirely of neutrons at high density—was first suggested by Zwicky[23] and Baade[24] in 1934,

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[20] Rapid neutron capture, leading to high-mass-number isotopes of heavy elements.

[21] Uncertainty in the masses results from not knowing the amount of spin the objects have.

[22] If a black hole were immediately formed by the merger, there would be less ejecta than observed.

[23] Fritz Zwicky (1898–1974), Swiss-American astrophysicist.

[24] Walter Baade (1893–1960), German-American astronomer.

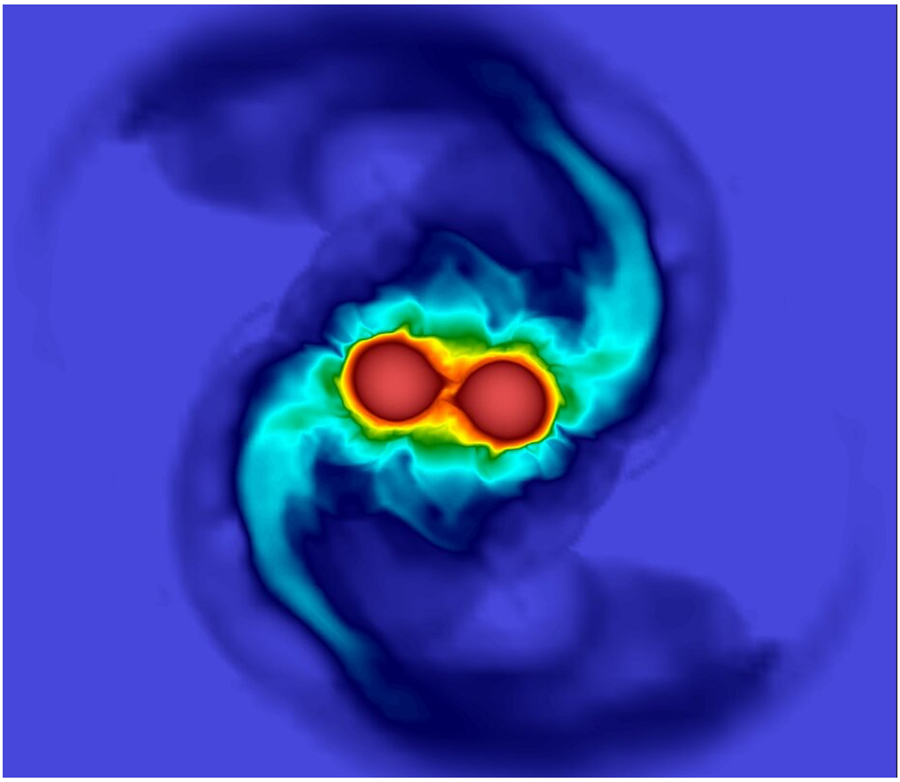

Figure 1.11. Numerical relativity simulation of two merging neutron stars similar to GW 170817. Image credit: Patricia Schmidt and Geraint Pratten (University of Birmingham); the Einstein Toolkit (https://einsteintoolkit.org/).

shortly after the discovery of the neutron itself by Chadwick.[25] Zwicky and Baade even predicted that the collapse of a star into a neutron star with the conversion of significant mass into energy would explain supernovae; however, at this time, the idea was purely hypothetical, and it seemed unlikely that such an object could ever be detected—they would be so small and so cold that there would be no significant thermal emission from them.

It took the development of radio astronomy, with its sensitivity to nonthermal emission, for neutron stars to be observationally confirmed, in the form of pulsars. Hewish[26] and Bell[27] designed and built a radio telescope (the Interplanetary Scintillation Array), which they were using to study the newly discovered quasars. The telescope was designed to work in the time domain (using chart recorders), so it recorded the regular arrival of radio pulses from one point in the sky. Bell's persistence in tracking down this periodic signal led to the

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[25] James Chadwick (1891–1974), British physicist.

[26] Antony Hewish (1924–2021), British astrophysicist, winner of the Nobel Prize in Physics 1974.

[27] Jocelyn Bell Burnell (1943–), British astrophysicist.

discovery of pulsars (Hewish et al. 1968).[28] By the time of the discovery, theoretical models of radio pulses from neutron stars had been put forward independently by Pacini[29] and by Gold.[30] These rotating neutron star models were the only ones that could account for the very short rotation period of the Crab Pulsar (33 ms), measured in 1968.

While the astronomical heritage of pulsar astronomy lies in the radio part of the electromagnetic spectrum, pulsars play a role in multimessenger astronomy (see Section 7.5.3). As an early case of the importance of time-domain observations, they served as an early laboratory for the time-domain techniques that are key to many of the multimessenger observations we make now. Pulsars are extremely precise clocks, so the combination of signals from a pulsar timing array (PTA) may be able to detect the passing of gravitational waves in space—a very different approach to their detection. Gravitational waves may also be emitted from pulsars: Fast-spinning highly magnetized young neutron stars can have nonsymmetric rotational perturbations and may emit gravitational waves with frequencies of a few hundred Hertz—within the frequency range of ground-based detectors. Gravitational-wave detection would then probe the rotation and deformation of these compact objects (Chapter 9).

Neutron stars may also emit neutrinos, either as thermal emission in the MeV range (Chapter 8) or due to hadron acceleration processes in the magnetized wind or jet yielding GeV to EeV neutrinos. The high-energy neutrinos may therefore probe the highly magnetized winds (Kashiyama et al. 2016).

1.2.7.1 Pulsar Wind Nebulae

As the product of a supernova explosion, pulsars are often found within a cavity, surrounded by the shell of matter ejected by the explosion. Some pulsars, however, are surrounded by centrally concentrated pulsar wind nebulae (PWNs) or plerions; the prototype of these is the Crab pulsar.

PWNs are made up of highly relativistic leptons (electrons and positrons) from the neutron star wind; they are generally found around young pulsars with fairly high magnetic fields. The relativistic leptons emit synchrotron radiation across a very broad spectrum from radio to X-rays, and gamma rays (up to TeV energies) by inverse-Compton emission. PWNs usually appear within a few hundred years after a pulsar's creation and last about 100,000 years. They can be seen in visible light, but most observations are carried out in the radio continuum (Chapter 2), soft X-rays, hard X-rays (Chapter 6), and gamma rays (Chapter 7; Section 7.5.2). Although observed in electromagnetic radiation, PWNs are sources of high-energy leptonic cosmic rays.

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[28] The discovery of at least four such sources in different parts of the sky made it unlikely that these were signals from alien civilizations.

[29] Franco Pacini (1939–2012), Italian astrophysicist.

[30] Thomas Gold (1920–2004), Austrian–British–American astrophysicist.

1.2.8 Ultra-high-energy Cosmic Rays

An ultra-high-energy cosmic ray (UHECR) has energy greater than 1 EeV (10^{18} eV), placing it among the highest-energy—and rarest—cosmic rays. These cosmic rays have energies comparable to macroscopic phenomena; an EeV is equivalent to 0.16 J.

Cosmic rays with energies $>5 \times 10^{19}$ eV (the Greisen–Zatsepin–Kuzmin limit or GZK limit) will lose energy by interaction with the photons of the cosmic microwave background, so this should be a practical upper limit to the cosmic-ray spectrum. However, particles with energy of order 10^{20} eV have been detected.[31] Such particles, known as extreme energy cosmic rays (EECRs), should have an effective range of about 50 Mpc due to the GZK limit, implying an origin within or near the Milky Way. The GZK limit is derived for protons, which make up the majority of cosmic rays. There is some evidence that the highest-energy cosmic rays are dominated by heavier nuclei up to iron (Anchordoqui 2019) but these have their own equivalents to the GZK limit, which are fairly similar in energy.

A fundamental question about UHECRs is simply how they are accelerated to such high kinetic energy. Acceleration theories fall into two basic categories: "One-shot" processes assume direct acceleration to high speed by an extended electric field, which could be produced by the rapid rotation of compact highly magnetized objects such as white dwarfs, neutron stars (pulsars), or black holes. The second category involves gradual energy gain through multiple stochastic encounters with moving magnetized plasmas, found on scales throughout the universe from local (the interplanetary medium) to galactic (e.g., SNRs, the Galactic disk and halo, and microquasar systems) and intergalactic (e.g., AGNs, jets and lobes of giant radio galaxies, blazars, GRBs, starburst superwinds, and clusters of galaxies). Stochastic methods, which by definition are probabilistic and random, are relatively slow and inefficient. Other hypothetical sources of these cosmic rays include hypernovae, relativistic SNe, the decay of supermassive particles from the early universe, dark matter particle decay, and even compact stars composed of conjectured subcomponents of quarks and leptons called preons.

The major detector experiment focused on UHECRs is currently the Pierre Auger Observatory in Argentina. Other projects include the Telescope Array in Utah (successor to the Fly's Eye experiment and the Japanese AGASA) and TAIGA in Siberia. Innovative detection methods using radar and even distributed mobile phones have also been proposed to find these very rare events. Space-based detection, by monitoring of Earth's atmosphere, has also been proposed, such as the Probe Of Extreme Multi Messenger Astrophysics (POEMMA) concept, designed to find the air showers produced by UHECRs with energy >20 EeV.

UHECRs can also produce high- and ultra-high-energy cosmic neutrinos (Anchordoqui 2019), as well as the neutrinos produced when UHECRs enter

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[31] The "Oh-My-God particle," for example, was found on 1991 October 15 over Utah by the "Fly's Eye" experiment, with energy 3.2×10^{20} eV.

Earth's atmosphere. A multimessenger (cosmic-ray/neutrino) approach may be fruitful in identifying cosmic accelerators throughout the universe (Chapter 8).

1.2.9 Tidal Disruptive Events

Tidal disruptive events (TDEs) occur when a star becomes close enough to a supermassive black hole so that the star is ripped apart by the black hole's tidal forces[32] (Chapter 9). All black holes have a tidal disruption radius, but for stellar-mass black holes, it lies within the Schwarzschild radius. For supermassive black holes, the tidal disruption radius lies outside the Schwarzschild radius, so a star can be tidally disrupted without disappearing completely into the black hole.

There are a few dozen TDE candidates identified from wide-field optical and UV transient surveys, as well as X-ray telescope observations (Dai 2018). Interestingly, some distinct classes of TDEs have been observed; some radiate in the near UV and optical while others have prominent X-rays. Some also have relativistic jets. Unified models have been proposed for these different classes of TDEs in which the spectral properties depend on the viewing angle of the observer to the disk.

For example, ASASSN-19bt was detected by the All Sky Automated Survey for SNe project on 2019 January 21. The star was destroyed by a black hole in 2MASX J07001137–6602251, a galaxy 115 Mpc away (Holoien et al. 2019). UV observations with the Swift satellite showed a drop from 40,000 to 20,000 K over a period of a few days near the same time.

Although the disk associated with these SMBHs should obey a maximum accretion rate known as the Eddington limit due to light pressure, models have predicted emission beyond soft X-rays. This gives rise to the concept of super-Eddington accretion and may yield energies up to gamma rays. The mechanism of Super-Eddington accretion is not understood at this time.

Therefore, given the high-energy environments of SMBHs, the tidal disruption and accretion of stellar matter could produce many different messengers in the electromagnetic realm from radio to gamma rays as well as neutrinos and possibly cosmic rays.

1.2.10 Soft Gamma Repeaters

On 1979 March 5, a powerful wave of gamma radiation was detected by multiple satellites—100 times stronger than the GRB detected by the Vela satellites in 1967. This burst was only a fraction of a second long but had as much energy as the Sun emits in 10,000 years. This first peak was followed by a 100 s tail with periodic repeating peaks.

Several of these events have now been detected. They are termed soft gamma repeaters (SGRs), which are defined to emit large bursts of gamma rays and X-rays at irregular intervals and are associated with a type of neutron star called a magnetar (Section 1.2.10.1).

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[32] The tidal force elongates the material, stretching it in one dimension and compressing it in the others, hence the term "spaghettification."

1.2.10.1 Magnetars

Magnetars are a type of neutron star with extremely powerful magnetic fields ($\approx 10^{13}$–10^{15} G) that can decay and give rise to high-energy emission of X-rays and gamma rays. Magnetars rotate relatively slowly every 2–10 s. While the magnetic field can emit strong bursts of X-rays and gamma rays, their fields decay after 10^4 years. Gamma-ray flares may occur also, which may be the result of starquakes. It is important to note that magnetars may not be pulsars[33] (Figure 1.12).

The origins of magnetars are theorized to result from a magnetohydrodynamic dynamo process inside the neutron star. It is hypothesized that the inside of these young neutron stars remained an ordinary fluid at 30 billion K for a short time. This neutron fluid could bob up and down at thousands of kilometers per second. If the initial magnetic field is strong enough and the rotation is more than 200 per second, a few seconds of the dynamo effect will amplify the magnetic field to greater than 10^{15} G.[34]

According to models, the stronger the initial magnetic field, the faster the pulsar will die. The high magnetic field causes the pulsar's rotation period to slow down dramatically and rapidly. Thus, magnetars are born spinning faster than a typical pulsar, but the stars' rotational energy is quickly lost. For a field of 10^{15} G, a magnetar might slow to a period of about 8 s.

Eight seconds was the periodicity of the SGR event observed on 1979 March 5 (SGR 0525–66), suggesting a connection between magnetars and SGRs. The origin of this event was traced to the LMC and associated with a 5000 year old remnant known as N49 in the LMC. This particular SGR was intensely bright with a tail of regular pulses that was thought to occur because the magnetic fields and the remainder of the outburst were dragged out as the neutron star rotated. Each time it faced Earth, a pulse was detected.

The huge energy associated with SGR 0525–66 required the field to be stronger than 10^{14} G. It is suspected that when an extremely strong field drifts through the solid, relatively stable crust of a neutron star, the twisting and turning creates a starquake. It is the twisting of the magnetic field outside the star energizing electrons and positrons that trigger hard gamma rays. The pulsating tail was powered by the residue of a dispersing shrinking hot cloud of electron–positron pairs trapped by the stars' magnetic field. This residue cools down as escaping X-rays also. In these strong magnetic fields, X-ray photons may split in two and atoms can become long and thin; the polarization of hard X-rays may also occur (Moskvitch 2020).

It has also been proposed that gravitational-wave bursts may be detected at the time of SGR flares, as well as long-lived quasiperiodic[35] waves after the

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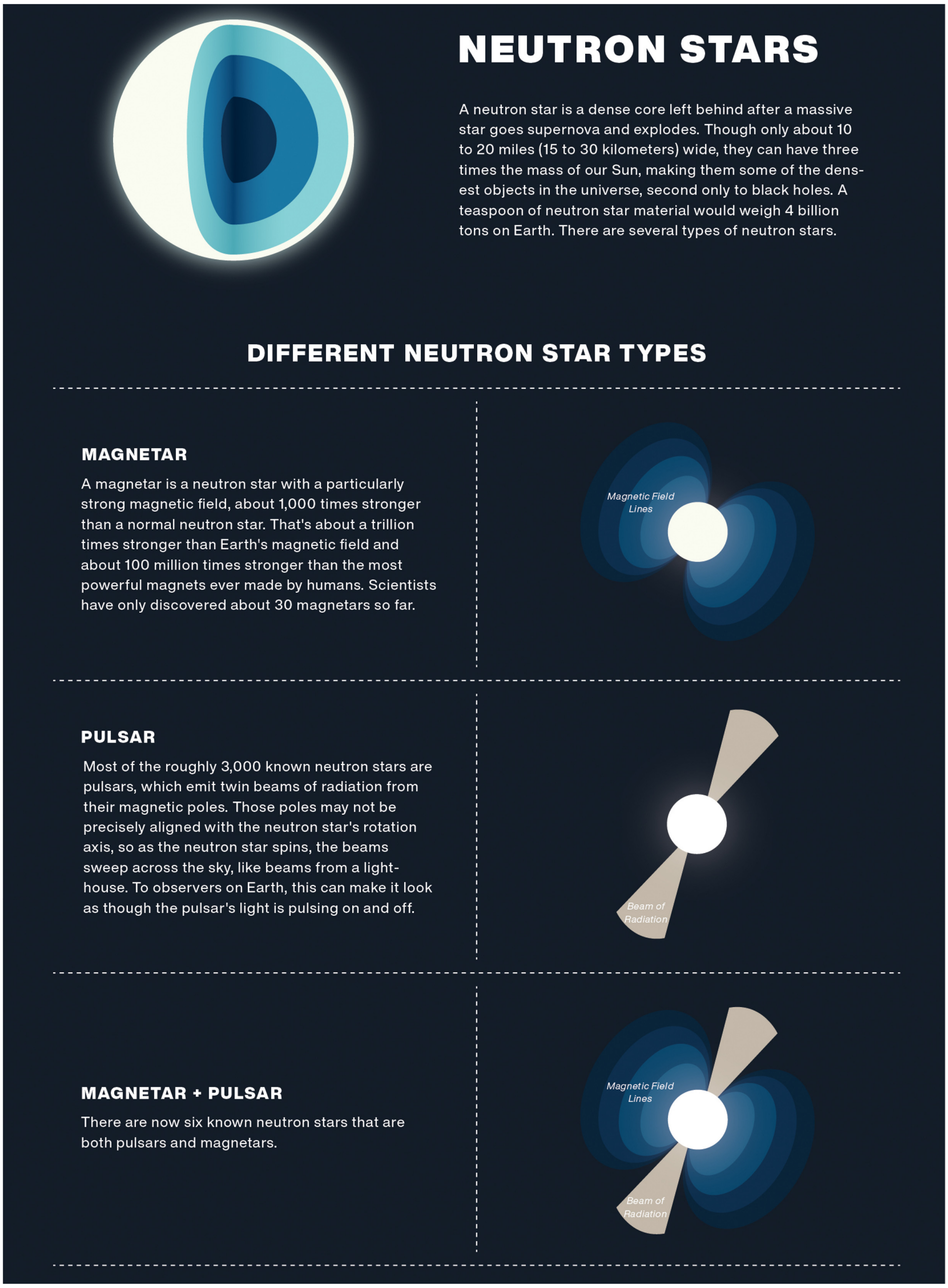
[33] An excellent reference list about magnetars with article links can be found at https://en.wikipedia.org/wiki/Magnetar.

[34] For reference, a refrigerator magnet is about 100 G.

[35] Quasiperiodic behavior is a pattern of recurrence with a component of unpredictability that does not lend itself to precise measurement.



NEUTRON STARS

A neutron star is a dense core left behind after a massive star goes supernova and explodes. Though only about 10 to 20 miles (15 to 30 kilometers) wide, they can have three times the mass of our Sun, making them some of the densest objects in the universe, second only to black holes. A teaspoon of neutron star material would weigh 4 billion tons on Earth. There are several types of neutron stars.

DIFFERENT NEUTRON STAR TYPES

MAGNETAR

A magnetar is a neutron star with a particularly strong magnetic field, about 1,000 times stronger than a normal neutron star. That's about a trillion times stronger than Earth's magnetic field and about 100 million times stronger than the most powerful magnets ever made by humans. Scientists have only discovered about 30 magnetars so far.

PULSAR

Most of the roughly 3,000 known neutron stars are pulsars, which emit twin beams of radiation from their magnetic poles. Those poles may not be precisely aligned with the neutron star's rotation axis, so as the neutron star spins, the beams sweep across the sky, like beams from a lighthouse. To observers on Earth, this can make it look as though the pulsar's light is pulsing on and off.

MAGNETAR + PULSAR

There are now six known neutron stars that are both pulsars and magnetars.

Figure 1.12. Different neutron star types. Image credit: NASA/JPL.

giant flare. Also, given that these magnetars have huge magnetic fields, they may well be cosmic-ray accelerators or produce gamma rays up to TeV energies; even high-energy neutrinos could also be produced (Halzen et al. 2005).

1.3 Conclusion

In this chapter, we have introduced the more practical aspect of multimessenger astronomy by discussing a multitude of astrophysical events; including some history of the evolution of our understanding. As was the case for the concept of multiwavelength astronomy, multimessenger astronomy will give us another order of magnitude of insight into astrophysical processes in the near and distant universe.

As discussed in this chapter, three major confirmations of multimessenger events beyond the Milky Way include (Moskvitch 2020):

- The detection of SN 1987A using both optical telescopes and neutrino observatories.
- The location of the origin of a cosmic neutrino, 170922A, to a blazar, TXS 0506+056, 3.8 billion lt-yr away using optical telescopes and the IceCube neutrino observatory.
- The detection and observation of GW 170817 and EM 170817 in multiple wavelength domains.

Finally, we also mention the Astrophysical Multimessenger Observatory Network (AMON; https://www.amon.psu.edu/) as a currently unique virtual observatory that has been built with the purpose of enabling near real-time coincidence searches using data from leading multimessenger observatories and astronomical facilities (Ayala Solares et al. 2020). Given the astrophysical processes in the zoo of events outlined here, it is obvious that in practice, multimessenger astronomy is rapidly improving our insight into high-energy events within the universe.

References

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, PhRvL, 119, 161101
Aiello, S., Akrame, S. E., Ameli, F., et al. 2019, APh, 111, 100
Aiello, S., & Albert, A. 2021, EPJC, 81, 445
Alsaberi, R. Z. E., Barnes, L. A., Filipović, M. D., et al. 2019, Ap&SS, 364, 204
Anchordoqui, L. A. 2019, PhR, 801, 1
Ayala Solares, H. A., Coutu, S., Cowen, D. F., et al. 2020, APh, 114, 68
Bannister, K. W., Deller, A. T., Phillips, C., et al. 2019, Sci, 365, 565
Bozzetto, L. M., Filipović, M. D., Urošević, D., Kothes, R., & Crawford, E. J. 2014, MNRAS, 440, 3220
Bozzetto, L. M., Filipović, M. D., Vukotić, B., et al. 2017, ApJS, 230, 2
Britzen, S., Fendt, C., Böttcher, M., et al. 2019, A&A, 630, A103
Burke-Spolaor, S. 2018, NatAs, 2, 845
Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Natur, 541, 58
Clesse, S., & Garcia-Bellido, J. 2020, arXiv:2007.06481
Dai, L. 2018, ApJ, 859, L20
Fryer, C. L., Burns, E., Roming, P., et al. 2019, BAAS, 51, 122
Gendre, B., Stratta, G., Atteia, J. L., et al. 2013, ApJ, 766, 30
Greiner, J., & Mazzali, P. A. 2015, Natur, 523, 189
Halzen, F., Landsman, H., & Montaruli, T. 2005, arXiv:astro-ph/0503348

Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., & Collins, R. A. 1968, Natur, 217, 709
Holoien, T. W. S., Vallely, P. J., Auchettl, K., et al. 2019, ApJ, 883, 111
Hurley-Walker, N., Filipović, M. D., Gaensler, B. M., et al. 2019a, PASA, 36, e045
Hurley-Walker, N., Gaensler, B. M., Leahy, D. A., et al. 2019b, PASA, 36, e048
Kashiyama, K., Murase, K., Bartos, I., Kiuchi, K., & Margutti, R. 2016, ApJ, 818, 94
Kembhavi, A., & Khare, P. 2020, Gravitational Waves: A New Window to the Universe (Singapore: Springer)
Kinugawa, T., Takeda, H., & Yamaguchi, H. 2019, arXiv:1910.01063
Kirsten, F., Snelders, M. P., Jenkins, M., et al. 2021, NatAs, 5, 414
Levan, A. 2018, Gamma-Ray Bursts (Bristol: IOP Publishing)
Li, C.-J., Chu, Y.-H., Gruendl, R. A., et al. 2017, ApJ, 836, 85
Maggi, P., Haberl, F., Kavanagh, P. J., et al. 2016, A&A, 585, A162
Maggi, P., Filipović, M. D., Vukotić, B., et al. 2019, A&A, 631, A127
Marcote, B., Nimmo, K., Hessels, J. W. T., et al. 2020, Natur, 577, 190
Margalit, B., & Metzger, B. D. 2018, ApJ, 868, L4
Moskvitch, K. 2020, Neutron Stars; The Quest to Understand the Zombies of the Cosmos (Cambridge, MA: Harvard Univ. Press)
Predehl, P., Sunyaev, R. A., Becker, W., et al. 2020, Natur, 588, 227
Roper, Q., Filipovic, M., Allen, G. E., et al. 2018, MNRAS, 479, 1800
Sano, H., Yamane, Y., Tokuda, K., et al. 2018, ApJ, 867, 7
Schnittman, J., Sigl, G., & Buonanno, A. 2006, in AIP Conf. Ser. 873, Laser Interferometer Space Antenna, ed. S. M. Merkovitz, & J. C. Livas (Melville, NY: AIP), 437
Scholtz, J., & Unwin, J. 2020, PhRvL, 125, 051103
Stanek, K. Z., Matheson, T., Garnavich, P. M., et al. 2003, ApJ, 591, L17
Tendulkar, S. P., Bassa, C. G., Cordes, J. M., et al. 2017, ApJ, 834, L7
Vattis, K., Goldstein, I. S., & Koushiappas, S. M. 2020, PhRvD, 102, 061301
Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507
Wright, W. P., Nagaraj, G., Kneller, J. P., Scholberg, K., & Seitenzahl, I. R. 2016, PhRvD, 94, 025026
Zhang, B 2020, Natur, 587, 45
Zuber, K. 2020, Neutrino Physics (3rd ed. Boca Raton, FL: CRC Press)