The Dawn of Multi-Messenger Astrophysics: Observations of a Binary Neutron Star Merger

多信使天文学的黎明：双中子星并合的观测

On August 17, 2017 astronomers around the world were alerted to gravitational waves observed by the Advanced LIGO and Advanced Virgo detectors. This gravitational wave event, now known as GW170817, appeared to be the result of the merger of two neutron stars. Less than two seconds after the GW170817 signal, NASA's Fermi satellite oberserved a gamma-ray burst, now known as GRB170817A. Within minutes of these initial detections telescopes around the world began an extensive observing campaign. The Swope telescope in Chili was the first to report a bright optical source (SSS17a) in the galaxy NGC 4993. Several other teams independently detected the same transient over the next minutes and hours. For the next several weeks astronomers observed this location with instruments sensitive across the electromagnetic spectrum. These observations provide a comprehensive view of this cataclysmic event starting ~100 seconds before merger until several weeks after. The observations support the hypothesis that two neutron starts merged in NGC 4993 producing gravitational waves, a short-duration gamma-ray burst, and a kilonova. GW170817 marks a new era of multi-messenger astronomy, where the same event is observed by both gravitational waves and electromagnic waves.

在2017年8月17日，许多分布在全球各地的天文学家们获知了一个消息，高新LIGO和高新Virgo探测器探测到了一个新的引力波信号。这一引力波事件，正式编号为GW17817，其形式与两个中子星的并合相一致。GW170817引力波信号到达之后不到两秒的时间内，NASA的费米卫星就探测到了一个伽马射线暴，命名为GRB170817A。在最初探测之后的几分钟内，全世界各地的望远镜就开始了忙碌的观测。在智利的Swope望远镜是第一个在星系NGC4993中报道观测到明亮的光学源（SSS17a）的。其他几个团队在接下来的几分钟到几小时内独立地探测到了这一个源。在接下来的几个星期内，天文学家在光谱不同波段上都投入了观测设备，在那一区域进行观测。这些观测对这一灾变性事件提供了从并合前约100秒到并合后数星期的全面的描述。这些观测验证了这一假设：NGC4993中的两个中子星并合，同时产生了引力波、短伽马暴和千新星。GW170817标志着多信使天文学的一个新时代，引力波和电磁波协同观测，一起研究同一个信号。

Introduction
简介

The idea of a neutron star (NS) was first presented over eighty years ago in 1934. It was another 33 years before they were observed. In 1967 X-ray emission from Scorpius X-1 was determined to be from a NS, and later the same year the first radio pulsar was discovered. Since then several binary neutron star (BNS) systems have been discovered, including the Hulse-Taylor binary, a BNS where one of the NSs is a pulsar. BNS have provided strong observational tests of General Relativity including the first firm evidence for the existence of gravitational waves (GWs). Since the early days of LIGO, BNS mergers have been consided a primary target for gravitational wave observations.

中子星的想法最初是在80多年前的1934年提出的。经过33年之后，才第一次被观测到。1967年，天蝎座X-1的X射线辐射被证认出来自一个中子星，而在同一年，第一个射电脉冲星被发现。从那时起，一些双中子星系统也陆续被发现，包括Hulse-Taylor双星，这是一个包含一颗脉冲星的双中子星系统。双中子星为广义相对论提供了极强的观测检验，包括支持引力波存在的第一个坚定证据。在LIGO发展的早期，双中子星并合被认为是引力波观测的首要目标。

In the mid-1960s gamma-ray bursts (GRBs) were discovered by the Vela satellites, and later established to be of cosmic origin. Determining the sources of GRBs has been one of the key challenges in high-energy astrophysics ever since. The idea that GRBs might be related to BNS mergers had been put forward early on. In 2005 the field experienced a breakthrough, when a short-duration gamma-ray burst (sGRB) was localized to a host galaxy, and multi-wavelength (X-ray, optical, radio) afterglows could be observed. These multi-wavelength observations provided evidence that sGRBs might be associated with BNS mergers or the merger of a NS with a black hole.

在20世纪60年代中期，伽马射线暴（伽马暴）被Vela（船帆座）卫星发现，在之后的研究中确立了其宇宙学起源。从此以后，确定伽马暴的来源就成了高能天体物理的关键问题。从很早开始，伽马暴可能与双白矮星并合相关的想法就已经提出了。在2005年，这个领域迎来了一次重大突破，一个短伽马暴被定位到一个宿主星系中，使得后续的多波段（X射线，光学，射电）余辉的观测称为可能。这些多波段观测证据表明，短伽马暴可能和包含中子星的并合事件有关，要么是两个中子星的并合，要么是一个中子星与一个黑洞并合。

A Multi-Messenger Discovery
多信使发现

On August 17, 2017 NASA's Fermi satellite and its Gamma-ray Burst Monitor (GBM) instrument sent an automatic alert about GRB170817A. It took about 6 minutes for automated LIGO data analysis to find that a candidate GW transient (later designated GW170817) had been detected at almost the same time at the LIGO-Hanford observatory. The GW was consistent with a BNS merger occuring less than 2 seconds before GRB170817A. The LIGO-Virgo rapid-response team manually inspected the data and issued an alert, reporting that a highly significant GW candidate was associated with the time of the GRB. Initial analysis of the data identified the area of the sky most likely to be the source of the GRB170817A and GW170817 signals, shown in Figure 1.

在2017年8月17日，NASA的费米卫星和它搭载的伽马暴监视器（GBM）设备自动发送了一个关于GRB170817A的警报。LIGO的自动数据分析用时6分钟，在LIGO 汉福德观测站的几乎同一时刻的数据中找到了一个引力波事件候选体（稍后命名为GW170817）这个引力波来自一个双中子星并合，发生于GWRB170817A之前两秒。LIGO-Virgo快速响应团队手动检查了数据，并随后发布了警报，报告了在伽马暴发生同时的一个高显著性的引力波候选体。如图1所示，初步的数据处理给出了GRB170817A和GW170817信号的可能天空来源位置。

This event marked the first GW multi-messenger discovery: it was observed by both GWs and electromagnetic (EM) waves. With the area of the sky identified from the GW and gamma-ray signal, telescopes around the world focused their effort to make further observations associated with this source. There were a plethora of key observations that occurred at different electromagnetic wavelengths, as well as neutrino fluence measurements. Figure 2 shows a timeline of the observations. The multi-wavelength observations were critical to the richness of this scientific discovery.

这个事件标志着第一次引力波的多信使探测：在引力波和电磁波同时进行探测。在从引力波和伽马信号认证出来的空间区域内，世界各地的望远镜倾尽全力开展了与源相关的后续观测。在不同的电磁波波段和中微子渠道上，有许多至关重要的观测。图2展示了各类观测的时间线。多波段的观测对于这一发现的科学内涵的丰富性居功至伟。

At the time of the alert for GW170817, the location of the source in the sky had set in Australia, but it was well placed for observing by telescopes in South Africa and Chile. In the first few hours of Chilean darkness, the Swope telescope identifiied an optical transient (SSS17a) in the galaxy NGC 4993. Over the next two weeks, a network of ground-based telescopes and space-based observatories followed up the initial detections, spanning the ultraviolet (UV), optical (O), and near infrared (IR) wavelengths. These observations carefully monitored the spectral energy distribution, revealing that this exceptional electromagnetic counterpart was a kilonova. This observation firmly connects kilonovae with BNS merger, providing evidence supporting the idea that kilonova result from the radioactive decay of the heavy elements formed by neutron capture during the BNS merger.

在GW170817发布警报的时候，其空间位置正对着澳大利亚的上方，但是南非和智利的望远镜也同时在观测。在智利黑夜的最初几个小时里，Swope望远镜在星系NGC4993里认证出了一个光学瞬变源（SSS17a）。在接下来的两个星期里，地面望远镜和太空望远镜组成的阵列从紫外、光学、近红外等波段追踪着最初的探测。这些观测仔细监视着信号的频谱能量分布，揭示着这一特殊的电磁对应体是一个千新星。这一观测坚定地将千新星和双中子星并合联系起来，对于千新星来源于中子星并合阶段，通过中子俘获形成的重元素的放射性衰变的这一物理图景，提供了可靠证据。

Following the kilonova, X-ray and radio observatories studied the source, recording an afterglow signal from the event. These observations revealed important information on the energy output of the explosion, the ejected material, and the environment of the merger. Neutrino observatories searched for coincident, high-energy neutrinos from the area of GW170817. Neutrinos are emitted in the relativistic outflow produced during the BNS merger. No neutrinos were identified that came from the direction of GW170817 and no supernova neutrino burst signal was detected coincident with the merger. Following the identification of the host galaxy of the event, an extended search for neutrinos in the direction of NGC 4993 was carried out for two weeks following the merger, but found no significant neutrino emission. It remains a goal of multi-messenger astronomy to detect gravitational waves, electromagnetic radiation, and neutrinos from the same cosmic event.

伴随着千新星，X射线和射电望远镜也同样研究着这一源，并记录到了来自该事件的余辉信号。这些观测揭示了关于这一爆发现象的能量输出、抛射物质、并合产物的外部环境等等信息。中微子观测在GW170817的空间范围附近也搜索着同时发生的高能中微子。在双中子星并合产生的相对论性外流中会产生中微子。然而，在GW170817方向上没有探测到中微子，在引力波信号同一时刻，也没有探测到来自超新星中微子的爆发信号。伴随着这一事件宿主星系的发现，开展了关于NGC4993方向的为期两周的深度中微子搜寻，然而还是没能找到显著的中微子辐射。在未来，来自同一天文事件的引力波、电磁波和中微子同时观测，依然是多信使天文学的目标。

Conclusions

结论

For the first time, both gravitational and electromagnetic waves from a single astrophysical source have been observed. This joint observation supports the hypothesis that the source is the merger of two neutron stars. It also allowed for the identification of the host galaxy. The electromagnetic observations comprise three major components at different wavelengths: (i) a prompt, short gamma-ray burst which demonstrates the association of at least a fraction of them with mergers of neutron star binaries, (ii) an ultraviolet, optical, and infrared transient due to the radioactive decay of heavy elements formed by neutron capture (kilonova) observed clearly for the first time, (iii) followed by delayed X-ray and radio counterparts. All of these observations provide the first global picture of the processes at play after compact star mergers that contain neutron stars, including a jet of high-energy particles and the interaction of this jet with the surrounding interstellar medium. This event also demonstrates the importance of collaborative, joint gravitational-wave, electromagnetic, and neutrino observations, and marks a new era in multi-messenger, time-domain astronomy.

有史以来，人类第一次同时观测到来自同一个天文事件的引力波与电磁波。这一联合观测支持了该源为双中子星并合的假说。同时，它也使宿主星系的认证称为可能。电磁波的观测主要由不同波段的三个主要成分构成：（1）一个快速、短暂的伽马射线暴，表明了至少这类事件的一部分是源于双中子星并合。（2）一个首次成功开展的对由中子俘获产生的重元素放射性衰变（千新星）紫外、光学和红外的瞬变源的观测。（3）稍后的X射线和射电对应体。所有的这些观测都第一次提供了一副关于包含中子星的双星并合后的完整物理图景，其中既有包含高能粒子的喷流，也有喷流与外部星际介质环境的相互作用。这一事件展示了联合着引力波、电磁波和中微子的不同研究团队之间的合作的重要性，也标志着多信使天文学与时域天文学的新时代。

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Glossary
术语表

Black hole: A region of space-time caused by an extremely compact mass where the gravity is so intense it prevents anything, including light from leaving.
Gamma rays: Electromagnetic radiation at the highest energy on the electromagnetic spectrum.
Neutrino: Tiny particles with no electric charge.
Neutron star: Extremely dense object which remains after the collapse of a massive star.

黑洞：由极端致密质量而引起的时空区域，其强大的引力甚至连光都无法逃脱。
伽马射线：在电磁波频段中最高能量的电磁辐射。
中微子：没有电荷的微小粒子
中子星：在大质量恒星塌缩后参与的极端致密天体

Artist's illustration of two merging neutron stars. The narrow beams represent the gamma-ray burst while the rippling spacetime grid indicates the isotropic gravitational waves that characterize the merger. Swirling clouds of material ejected from the merging stars are a possible source of the light that was seen at lower energies. Credit: National Science Foundation/LIGO/Sonoma State University/A. Simonnet.
艺术家关于两个并合中的中子星的想想。窄束代表着伽马暴，而扭曲的时空网格标志着由并合产生的个相同性的引力波。旋转的物质团块是从并合的双星中抛射出的物质，可能导致了较低能量的电磁信号源。版权：国家科学基金会/LIGO/索诺马州立大学/A. Simonnet

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GW170817 location on the sky.
GW170817的空间位置

Figure 1: Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows a projection of the 90% credible regions from LIGO (light green), LIGO-Virgo (dark green), triangulation from the time delay between Fermi and INTEGRAL (light blue), and Fermi GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hours after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right).
图1： 引力波、伽马射线和可见光的位置。左边的小格子展示了90%置信区间投影区域，分别来自LIGO（浅绿色），LIGO-Virgo（深绿色），来自费米与INTEGRAL时间延迟得到的三角定位（浅蓝色），费米GBM（深蓝色）。放大图展示了宿主星系NGC4993的位置，包括了来自并合后10.9小时的Swope光学发现图片（右上方）与在并合20.5天前的图片（右下方）。

Figure 2: The timeline of the discovery of GW170817, GRB170817A, SSS17a/AT2017gfo and the follow-up observations is shown by messenger and wavelength relative to the time of the gravitational-wave event. The sub plots are detailed one by one below.

GW170817观测时间线
图2：GW170817，GRB170817A，SSS17a/AT2017gfo发现的时间线，以及以信使、波长和相对于引力波信号时间排列的后续观测。小图是单独测量的具体细节。

Figure 2a: In the middle of Figure 2 is the timeline of the discovery and follow-up of this system. Two types of information are shown for each band/messenger. First, the shaded dashes represent the times when information was reported in a GCN Circular. The names of their associated authors is collected at the beginning of the row. Second, the solid lines with circles indicate when the source was detectable by at least one telescope in the particular band. The circle sizes are scaled approximately by magnitude.

图2a：在图2中部，是这一系统的发现与后续观测的时间线。对于每一个波段或信使都显示了两种信息。首先，阴影区域代表了在GCN通告里报告的时间。每行开头展示着对应的作者。其次，带圆圈的实线标志着该源在对应波段至少被探测到一次。圆圈的大小大致由星等校准。

Figure 2b: At the top left of Figure 2 is a spectrogram of the gravitational waves as seen in the LIGO-Livingston detector. Here we show the spectrograms from all three LIGO-Virgo detectors. You can see the characteristic "chirp", when the frequency increases, of a binary merger.

图2b：在图2的左上角展示了LIGO利文斯顿探测器探测到的引力波时频图。这里我们展示了所有三个LIGO-Virgo探测器的视频图。你可以看到标志性的双星并合的“啁啾”，频率随时间推移而增加。

GRB170817A light curve

GRB170817A 光变曲线

Figure 2c: At the top center of Figure 2 is a light curve of the initial gamma-ray detection GRB170817A by Fermi. This shows gamma ray counts as a function of time. The big spike is the GRB.
图2c：在图2上方中部，是一开始的Fermi发现的GRB170817A的伽马射线探测。它展示了不同时间上伽马射线探测数的不同。巨大的尖峰对应着伽马暴。

Figure 2d: At the top right of Figure 2 is a plot of 4 optical spectra taken at differnt times after the BNS merger. As time passes, the remnant cools, causing the spectrum to dim and change shape. Also shown on the plot in dotted lines are the expected thermal spectra of a black-body at two different temperatures.

图2d：在图2的上方右部，是在双中子星并合后不同时间拍摄的光谱。随着时间的推移，残余部分冷却，导致了光谱变暗，形状也改变。同时在图中展示的点线是两个不同温度的黑体辐射热谱。

Figure 2e: At the bottom of Figure 2 are 8 images of the afterglow of the BNS merger (designated SSS17a/AT2017gfo). On the left are six optical images taken between 10 and 12 hours after the merger by different telescopes. On the right are images constructed from x-ray and radio observations. The x-ray image was taken 9 days after the merger by NASA's Chandra X-ray Observatory. 16 days after the merger NRAO's Jansky Very Large Array (VLA) captured the radio image. In all 8 images the galaxy NGC 4993 is seen in the middle and SSS17a/AT2017gfo is marked by two lines.

图2e：在图2的底部展示着双中子星并合的8张余辉图片（编号SSS17a/AT2017gfo）。在左侧是并合后10到12小时不同望远镜拍摄的六个光学图片。X射线图片由NASA的钱德拉X射线天文台在并合9天后拍摄。并合16天后，NRAO的央斯基甚大阵（VLA）捕捉到了射电图像。在所有的8张图像中，可以看到NGC4993星系处于中间，而SSS17a/AT2017gfo用两条线标志。