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第 649 次学术讨论会 •中国空间引力波探测计划及国际协作联盟

激光干涉引力波空间阵列核心问题的综合讨论

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空间激光干涉引力波探测计划, 例如欧洲航天局主导和美国参加的 LISA(Laser Interferometer Space Antenna)计划[1]、中国的“太极”计划[2]和“天琴”计划[3]等, 瞄准中低频段(0.1 mHz~1 Hz)的引力波波源. 这个频段的引力波事件被认为具有更重要的天文学、宇宙学以及物理学意义[4~6], 其典型的波源包括超大(和中等)质量黑洞双星的并合、极端(和中等)质量比黑洞双星的绕转、银河系内数以百万计的致密双星系统以及随机引力波背景等.

地面激光干涉引力波天文台(Laser Interferometer Gravitational-wave Observatory, LIGO)于 2016 年成功探测到引力波信号[7], 证实了引力波的存在, 使得空间激光干涉引力波探测受到越来越多的关注. 引力波信号非常微弱以及空间任务的特殊性, 对空间激光干涉引力波探测的关键技术, 包括方案设计、轨道优化、星间激光干涉测距系统、无拖曳控制系统、数据处理等提出了极高的挑战[8]. 有关空间激光干涉引力波探测计划的综合论述请参考文献[8], 本文将对空间激光干涉引力波探测中存在的几个关键问题进行全面探讨.

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1　空间引力波探测现状

我国从 2008 年起就集中全国力量, 包括中国科学院、教育部和航天科技集团公司等优势单位, 开展空间引力波探测的探讨和研究. 2009 年, 中国空间引力波探测计划被列入中国科学院发布的中国至 2050 年空间科技发展路线图[9]; 2010 年, 我国首次提出空间引力波探测建议. 2011 年 8 月 24~26 日, 召开了主题为“空间引力波探测”的第 403 次香山科学会议. 2012 年, 受欧洲太空局邀请, 中国空间引力波探测团队出席了第一届 eLISA(Evolved Laser Interferometer Space Antenna)国际联合体会议, 并向全世界介绍了中国的空间引力波探测计划[10]. 2015 年, 我国发布了中国空间引力波的可行性方案, 并确定了 3×10^6 km 的臂长选择[11]. 经过多年的酝酿、调研和积累, 我国于 2016 年初提出了两个空间引力波探测计划[12]: 绕日心轨道的“太极”计划以及绕地心轨道的“天琴”计划. 其中, 空间“太极”计划由 3 颗以太阳为中心的卫星组成, 成正三角形编队, 三星的质心位于地球公转轨道上, 可落后地球约 20°. “太极”三星间距(臂长)为 3×10^6 km, 采用高精度星间激光干涉测距技术和无拖曳航天技术, 对中低频段的引力波进行探测和研究.

国际上, 最早的空间引力波探测项目是 1973 年提出的 LISA 计划, 也是二十余年来国际上发展最成熟的空间引力波探测计划. LISA 也采用日心轨道, 星间距最初设置为 5×10^6 km, 其敏感频段区域相对于“太极”偏低, 可以跟“太极”在探测频段上形成较好互补[13]. 2011 年, 由于 NASA(National Aeronautics and Space Administration)的退出, LISA 更名为 eLISA 计划, 又名 NGO(New Gravitational-wave Observatory)计划. 同时, 为缩减经费, 将臂长缩短为 1×10^6 km. 因此, 它的敏感频段略高于“太极”, 可以很好地衔接“太极”与地面引力波天线之间的探测频段[14]. eLISA 的技术演示卫星任务 LISA-Pathfinder 已于 2015 年 12 月成功发射, 并取得了超预期的结果[15]. 受 LISA-Pathfinder 成功发射的鼓舞, 2017 年, ESA(European Space Agency)宣布将引力波探测 LISA 计划正式列为欧洲第 3 个重大空间科学卫星项目, 计划于 2034 年发射; 同年, ESA 科学委员会同意接受 NASA 的回归申请, 再次跟 NASA 合作, 将 eLISA 改回 LISA, 并将臂长调整为 2.5×10^6 km[1]. 由于 LISA 和“太极”的臂长接近, 敏感频段基本相同, 因此探测的科学目标也与“太极”计划基本重合.

2 空间引力波探测计划科学目标讨论

2.1 空间引力波天线与地面引力波天文台的区别

自第一个引力波事件被探测以来，地面激光干涉引力波天文台已经发现了超过 19 个引力波事件[16]. 通过进一步升级，未来地面激光干涉引力波天文台对引力波事件的探测将成为常态[17]. 事实上，在执行地面引力波探测的同时，一直并行地在开展空间引力波探测计划.

其实，引力波信号跟电磁波信号一样，是一个宽频带的信息载体. 以电磁波天文望远镜为例，根据探测波长不同，电磁波天文望远镜分为微波望远镜、红外和近红外望远镜、可见光望远镜、紫外和深紫外望远镜、伽马射线和 X 射线望远镜等. 地面激光干涉引力波探测器，因其臂长短(千米量级)，只能探测中高频段(10 Hz~10 kHz)的引力波；空间激光干涉引力波天线，其臂长长，因此对中低频段(0.1 mHz~1 Hz)的引力波敏感. 而不同的频段对应的引力波波源也不一样. 地面激光干涉引力波探测器主要波源为小质量天体的扰动(1~100 太阳质量)，如黑洞-黑洞并合、中子星-中子星并合事件等. 空间激光干涉引力波天线的波源多为大质量天体的扰动(10^3~10^7 太阳质量)，如黑洞-黑洞并合，或者一个小型致密天体围绕大质量黑洞的绕转事件等.

2.2 空间引力波波源物理

空间激光干涉引力波探测的主要波源为超大(中等)质量黑洞的并合. 第一代恒星(Pop III stars)在死亡时会直接塌缩成一个数百或上千太阳质量的黑洞[18]，它们互相碰撞并合，慢慢成长为星系中心的超大质量黑洞. 这一成长过程中的黑洞并合事件都可以被未来的空间激光干涉引力波天线所捕获. 因此，对此类波源的探测步进可以帮助了解第一代恒星的演化，最重要的是可以揭示星系并合、演化以及宇宙大尺度结构形成的历史[19].

另一个主要波源是极端(中等)质量比黑洞绕转系统，它由一个超大(中等)质量黑洞和一个小致密天体组成. 这个绕转过程可以持续数年，支持长时间观测，可以进行长时间的信号积累；同时，小天体离中心黑洞非常近，可以看成一个检验粒子，对中心黑洞附近的强引力场进行全面扫描. 因此，这种波源提供了一个理想的天体实验室去研究黑洞附近的物理，从而让我们对引力本质有更深刻的认识[19,20]. 超大质量黑洞有相当大的概率捕获到一个致密双星系统. 这种波源频谱成分丰富，不仅有中低频段的信号，也有中高频段的信号，可以同时被空间激光干涉引力波探测天线和地面激光干涉引力波天文台捕获到[21].

其他引力波波源包括银河系内的致密双星系统，通过对它们的探测，可以了解致密天体在银河系内的分布，从而对银河系的历史以及银河系内恒星的演化进行研究. 随机引力波背景也是空间激光干涉引力波天线的波源，它主要包括宇宙大爆炸形成的原初引力波背景以及原初黑洞绕转和并合形成的背景引力波等，这些波源是研究宇宙起源、早期宇宙、引力本质和高能物理的极好对象[22~25].

3 空间激光干涉引力波探测方案问题讨论

3.1 轨道选择

目前空间激光干涉引力波天线有两类轨道选择：日心轨道和地心轨道. 其中日心轨道的优势是长周期稳定性好、卫星编队呼吸角小、太阳指向角稳定及卫星外热流稳定等[26]. 但是，为了保证轨道的长周期稳定，卫星编队需要远离地月系统的引力扰动，离地球约 5×10^7 km，由此带来一些技术挑战，比如深空测控、数传以及星间自动激光捕获等.

地心轨道的优势是便于卫星测控以及数据传输；同时，卫星入轨时间短，可以较快地开展科学探测. 但地心轨道受月球引力影响大，导致卫星编队轨道稳定性较差；同时，采用地心轨道，卫星会交替进入太阳阴影区和太阳照射区，因此卫星外热流不稳定，对整星热控提出了很大的挑战[27,28].

3.2 臂长选择

空间激光干涉引力波天线的臂长选择直接决定了其敏感频段，也就决定了其主要波源类型及波源对应的科学目标[11,29,30]. 臂长的细小变动(例如从 3×10^6 km 变为 5×10^6 km 或 1×10^6 km)，会对特定波源(例如中等质量黑洞)的探测事件率产生显著影响[11]. 因此，臂长的选择对最终空间激光干涉引力波天线的科学产出起着至关重要的决定性作用.

同时，对于相同强度的引力波信号而言，臂长较短则引力波引起的位移变化信号更小，从而对测量系统的测量精度要求更高[31]. 不过，短臂长(1×10^5~5×10^5 km)的空间激光干涉引力波天线可以起到连接长臂长空间引力波天线和地面引力波天文台的桥梁作用，并且在这个频段其他引力波波源较少，是用于观测宇宙大爆炸遗留的引力波背景的最好窗口[32,33].

4 空间激光干涉引力波探测关键技术讨论

4.1 激光干涉测距系统

空间激光干涉引力波天线是一个超精密的测量系统. 它以测试质量为引力波传感器，利用高精度激光干涉测距系统测量由引力波引起的相距数百万千米的两个自由测试质量间的皮米级距离变化，从而反演引力波信号(图 1)[8,13].

高精度星间激光干涉测距系统采用外差干涉[34]和弱光锁相[35]作为基本测量原理，其主要构成包括超稳空间激光器、超稳空间激光望远镜、高精度多功能星间激光干涉仪以及高精度数字相位计. 其中，激光器普遍采用 1064 nm

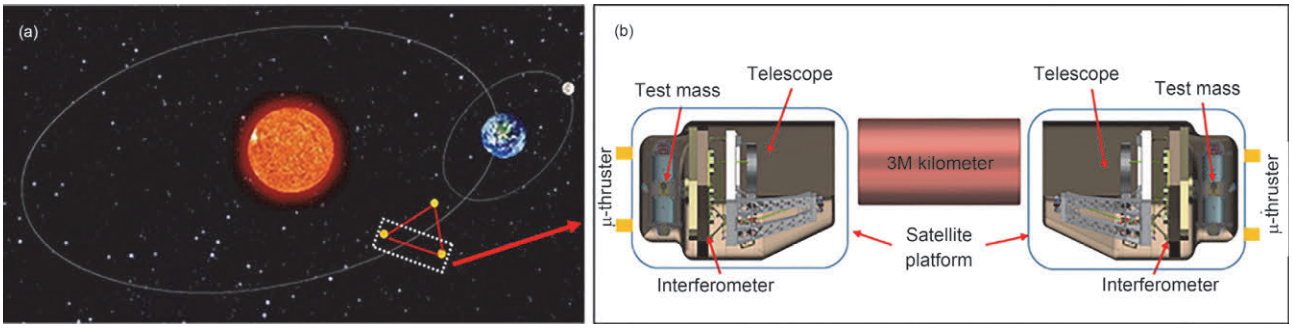

图 1 (网络版彩色)空间激光干涉引力波天线轨道(a)及载荷示意图(b)(以日心轨道为例)

Figure 1 (Color online) Schematic diagram of the orbit (a) and the payload (b) of the space-borne laser interferometer gravitational wave antenna (taking heliocentric orbit as an example)

波长[36,37]，并通过 Pound-Drever-Hall 方案将其频率稳定性预稳在 30 Hz/Hz$^{1/2}$[38]．望远镜采用超低膨胀系数材料制作，以保证其结构稳定性，同时采用离轴设计，降低杂散光[39,40]．干涉仪也采用超低膨胀系数材料制作，保证干涉仪本身由温度涨落产生的光程噪声小于 1 pm/Hz$^{1/2}$[41,42]．相位计一般采用 FPGA(field-programmable gate array)作为硬件载体，对干涉信号的相位进行读取，相位读取精度需达到 $2\pi\times10^{-6}$ rad Hz$^{1/2}$[43,44]．为使得星间激光干涉测距系统的噪声满足空间引力波探测的需求，还需要采取措施对激光指向噪声、激光频率噪声和时钟频率噪声进行压制和消除[45~55]．同时，为满足激光干涉测距系统的正常工作，干涉仪还需集成激光捕获[56,57]以及星间测距、通信和对钟[58]等功能．

4.2 无拖曳控制系统

外界干扰会扰动测试质量，造成测试质量间距离的变化，干扰引力波信号的探测．因此，需要对测试质量进行保护和隔离，使其处于自由悬浮状态．无拖曳航天技术[59]是利用航天器将测试质量保护在航天器内的惯性传感器中心．当航天器受到外界扰动力影响时，会引起航天器与测试质量间的距离变化，惯性传感器可以精确读出这个变化并发送至无拖曳控制系统．无拖曳控制系统对安装在航天器上的微推进器发送指令，命令微推进器推动航天器使得测试质量始终位于惯性传感器平衡位置．在整个科学任务的周期中，卫星平台始终要为测试质量提供超稳超静的环境．维持测试质量的加速度扰动始终低于 3×10^{-15} m s^{-2} Hz$^{-1/2}$ 的水平[8,13]．

无拖曳控制系统包括惯性传感器、微推进器和无拖曳控制器系统 3 大部分．其中，惯性传感器是无拖曳控制系统的传感机构，为了达到引力波探测的要求，其加速度读出噪声应低于3×10^{-15} m s^{-2} Hz$^{-1/2}$ [60,61]．微推进器可有多重选择，比如 FEEP[62], RIT[63,64]，胶体[65]，冷气[66]以及霍尔[67]等，要求微推进器分辨率≤0.1 μN，噪声水平≤0.1 μN/Hz$^{1/2}$[68]．无拖曳控制器是连接传感器和推进器，闭环整个无拖曳控制回路的关键．在空间激光干涉引力波探测任务中，需要优先关注测量频段内检验质量的残余扰动加速度，同时要求尽量减少推进器燃料的消耗[61,69,70]．

4.3 其他关键技术问题

空间激光干涉引力波天线是一个高复杂性的科学任务．系统复杂性引申出一系列问题有待深入研究：如何解决海量信号中单一信号的提取问题，如何深度挖掘现有波源的科学意义，如何优化科学目标而降低载荷指标要求，如何优化任务设置从而增强其科学意义，如何通过编队整体优化提升任务的探测灵敏度，以及面对如此复杂的耦合系统如何优化飞行器系统设计，如何突破二代时间延迟干涉技术(time delay interferometry, TDI)并解决复杂系统数据处理中的噪声问题等．同时，考虑建立一个终端至终端的空间激光干涉引力波探测数值仿真平台[71]，帮助理解和解决上述由复杂系统引出的科学问题．

5 总结与展望

空间引力波探测还可以覆盖从宇宙演化极早期的 TeV 能标的物理过程到现如今银河系中的致密双星绕转，从黑洞视界附近的极小尺度到宇宙演化的极大尺度，其可探测对象存在于几乎整个宇宙空间．总体而言，空间引力波探测的研究对象囊括了由近到远、由小到大的极为丰富的引力波源，探测的范围可以覆盖整个宇宙空间，对部分波源有各种引力波探测方式中最高的信噪比和最多的信号周期，有望在基础物理、引力波天文学和宇宙学研究中发挥关键的作用．

同时，空间引力波探测对技术要求极高，且涉及光学、电子、工程机械、航空航天等诸多领域．通过开展空间引力波探测，必将全面推动高精度空间惯性传感器、星间激光干涉测量、高精度卫星编队、卫星姿态、轨道、温度、星间通信、测距和对钟等各方面高精度控制技术的成

熟，带动一系列对国民经济和国家战略需求有重要价值的关键技术的发展. 上述技术的发展对于高精度全球时空坐标体系建立和全球重力场模型的建立，促进未来其他的前沿空间科学实验等均具有重要意义.

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Summary for "激光干涉引力波空间阵列核心问题的综合讨论"

Overall discussion on the key problems of a space-borne laser interferometer gravitational wave antenna

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Unlike their ground-based counterparts, space-borne laser interferometer gravitational wave detection missions focus on the gravitational wave sources in the lower frequency band between 0.1 mHz and 1 Hz. Various gravitational wave sources in such a frequency band are believed to be of considerable interest in astronomy and cosmology. The typical gravitational wave sources of a space-borne laser interferometer gravitational wave antenna are the super (intermediate) mass black hole merger, extreme (intermediate) mass ratio in-spiral, galactic binaries of compact stars, and stochastic gravitational wave background. The gravitational wave sources within the 0.1 mHz–1 Hz frequency band can help us understand the mystery of the universe's structural formation, evolution of massive black holes and its harbored galaxies, nature of gravity near the horizon of these massive black holes, and history of the early universe beyond the cosmic microwave background. To design a mission to achieve the abovementioned scientific impacts, considerable attention should be paid to several issues, such as orbital design and arm-length choice. The success of a space-borne laser interferometer gravitational wave detection mission requires a pico-meter precision inter-satellite laser ranging interferometer system and a state-of-the-art drag-free control system because of the weakness of the gravitational wave signals. The inter-satellite laser ranging interferometer system comprises four subsystems: stable laser source, stable laser telescope, ultra-precise laser interferometer, and ultra-precise phasemeter. Techniques, such as arm-locking, time-delay interferometry, sideband scheme, differential wave-front sensing, and pointing control, should be employed to suppress the laser frequency noise, clock frequency noise, and laser pointing jitter noise. Additionally, the ultra-precise laser interferometer needs to integrate the following functionalities: laser acquisition, laser ranging, laser communication, and clock synchronization. Conversely, the drag-free control system has the following three components: inertial sensor, micro-thruster, and drag-free controller. The inertial sensor is used to sense the displacement between the spacecraft and proof mass and send the signal to the drag-free controller. Further, the controller commands the micro-thruster to push the spacecraft to maintain the proof mass' position centered at the electrostatic cage of the inertial sensor. The space laser interferometer gravitational wave antenna is also a highly complex system in debt of the high degree of coupling between a subsystem and the high confusion of the enormous quantity of signals. An end-to-end numerical simulator might be essential in helping us understand the problems of data analysis, optimization of the configuration of the spacecraft and payload, and optimization of the mission design to solve the problem caused by complexity and to enhance the scientific output. Additionally, a more careful investigation of the levels 1 and 2 data analyses investigating the scientific impacts of the gravitational wave sources is also needed. The key problems of the abovementioned space-borne laser interferometer gravitational wave detection missions are generally discussed. Moreover, a brief history of the space-borne laser interferometer gravitational wave detection missions, including LISA, which is the ESA-NASA joint space-borne gravitational wave antenna; Taiji, which is the space-borne gravitational wave mission proposed by the Chinese Academy of Sciences; and TianQin, which is a geocentric orbit space-borne gravitational wave mission raised by Sun Yat-sen University, is reviewed. Finally, the conclusions and future prospect of the Chinese space laser interferometer gravitational wave detection missions are outlined.

space laser interferomter gravitational wave detection, inter-satellite laser ranging interferomter, drag-free control system, gravitational wave astronomy, theoretical and experimental relativity

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