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环境介质中左旋葡聚糖记录与植被火燃烧变化研究进展

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摘要 左旋葡聚糖主要来源于植物体纤维素在植被火燃烧发生时的高温热裂解过程, 化石燃料燃烧的贡献极低, 在环境研究中通常被作为示踪植被火燃烧的分子标志物. 左旋葡聚糖研究在近年来备受关注, 对地表环境介质中左旋葡聚糖记录及其对植被火燃烧变化的指示意义获得了如下主要认识: 气溶胶中的左旋葡聚糖能够反映从事件至季节尺度的植被火燃烧变化, 雪冰和沉积物中的左旋葡聚糖记录则能够揭示从季节至冰期-间冰期尺度的植被火燃烧变化规律. 因此, 左旋葡聚糖有望成为地表环境介质中指示植被火燃烧变化的可靠代用指标, 但涉及其稳定性、在冰芯与沉积物中记录解析、与其他环境代用指标的对比等方面还需要进一步加强研究.

关键词 左旋葡聚糖, 植被火燃烧, 气溶胶, 水体, 雪冰, 沉积物

以森林火灾为代表的植被火燃烧(vegetation fire), 通常也称作生物质燃烧(biomass burning), 是发生在地表的剧烈氧化过程[1~4]. 自陆生植物出现以来, 植被火燃烧就成为地球气候与环境演变中不可或缺的重要因子[1,5]. IPCC(Intergovernmental Panel on Climate Change)[6]第六次评估报告认为, 在当前气候变暖的情景下, 全球植被火燃烧灾害事件发生的风险将显著增加, 理解火燃烧规律和发生机制对预测未来植被火燃烧变化就显得十分必要. 植被火燃烧会快速释放热量并产生大量的温室气体和气溶胶成分, 会对全球地表生态结构、气候系统和人类社会等多方面产生重要影响[1~10]. 譬如, 植被火燃烧是地表植被演替的重要驱动因素[1,3,5], 烟尘也是人类呼吸道和心血管疾病的主要诱发因素等[11]. 据估算, 20世纪以来全球每年植被火燃烧面积大约是4×10^6 km^2[7,12], 每年产生的碳排放量高达2000 Tg(百万吨)以上[7,9], 超过人类碳排放总量的20%, 是地表系统中碳循环的重要组成部分. 植被火燃烧烟尘气溶胶在热对流作用下可以被传输至对流层顶部甚至平流层高度[13~15], 能够对全球气候产生重要影响[6,13,15]. 植被火燃烧烟尘气溶胶化学组成成分复杂, 主要包括黑碳、有机碳、特征离子(如K^+、NH_4^+等)、多环芳烃、小分子有机酸、酮类、醛类、酚类和左旋葡聚糖等[2,16~20]. 通过对地表不同环境介质中代表性成分的研究, 能够为理解全球变化背景下植被火燃烧历史变化特征、火燃烧碳排放与火燃烧的未来变化预测等问题提供一些重要的科学依据[2,17,21,22].

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左旋葡聚糖(1,6-脱水-β-D-吡喃葡萄糖, levoglucosan)主要来自于植物体纤维素在火燃烧温度高于300°C时的高温热裂解过程, 在地表环境中广泛存在且具有较好的稳定性[23], 通常被作为示踪植被火燃烧排放的分子标志物[16,24]. 本文综述了左旋葡聚糖的主要来源、在大气-水体-雪冰和沉积物等主要环境介质中的记录与其揭示植被火燃烧变化的研究, 以对左旋葡聚糖的产生、传输、沉积与记录形成较为系统的科学认识. 考虑到不同环境介质中左旋葡聚糖含量的检测方法已被系统评述[23~26], 本文不再赘述.

1 左旋葡聚糖及主要来源

左旋葡聚糖主要来自于植物体纤维素和半纤维素在火燃烧时的高温热裂解过程[16,18,23]. 纤维素和半纤维素是由葡萄糖组成的大分子多糖, 是植物体细胞壁的主要结构成分[18], 通常能够占植物体碳含量的50%以上[27]. 燃烧温度是影响左旋葡聚糖生成的主要因素[28]. 植被火燃烧发生时, 燃烧温度升高会伴随着植物体纤维素的水解、氧化、脱水和裂解等过程[29]. 燃烧温度低于300°C时, 纤维素经过解聚、脱水、碎片化和氧化等过程, 此时左旋葡聚糖产量较低; 燃烧温度在300°C左右时, 经过转糖基化键裂、裂变和歧化反应等过程, 形成左旋葡聚糖及其同分异构体半乳聚糖和甘露聚糖[16,23,30].

不同植物体在燃烧时的左旋葡聚糖排放系数(emission factor, 左旋葡聚糖/燃料干物质量的比率)存在明显差异[9,16,31]. 森林火灾等野火燃烧的左旋葡聚糖排放系数可高达1000 mg kg^{-1}以上, 泥炭、居民用薪材燃料和牛粪等燃烧的左旋葡聚糖排放系数可达500 mg kg^{-1}左右[9,31]. 利用实验室燃烧控制燃烧实验得到的薪材燃烧的左旋葡聚糖排放系数约在1000 mg kg^{-1}水平[32]. 除植物体纤维素外, 尽管有报道包括褐煤[33]和煤燃烧[34]等也会排放左旋葡聚糖, 但煤燃烧的排放系数大多低于10 mg kg^{-1}[31], 比植物体纤维素燃烧的排放系数低了1~3个数量级. 据估算, 燃煤对中国北方地区$PM_{2.5}$中左旋葡聚糖的贡献在0.5%以下[34].

基于GEOS-Chem全球三维化学输运模型(GEOS-Chem global 3-D chemical transport model)的模拟结果表明, 全球每年的左旋葡聚糖排放量约为3.8 Tg, 其中森林火灾等野火燃烧排放约为1.7 Tg, 秸秆焚烧等生物燃料排放约为2.1 Tg[31]. 中国区域2014年的左旋葡聚糖排放量大约为145 Gg[32]. 然而, 模型模拟主要是依据生物质燃烧源排放系数和生物质燃烧量的估算, 结果存在较大的不确定性. 比如, 在充分考虑大气降解的情况下, 依据GEOS-Chem模型模拟得到的青藏高原地区大气中左旋葡聚糖含量可高达50~100 ng m^{-3}(若不考虑大气降解, 则远超过100 ng m^{-3})[31], 比实际野外观测结果高了约1~2个数量级[35,36].

不同种类生物质燃烧产生的左旋葡聚糖及其同分异构体之间的比率存在明显差异[30,37,38](图1). 通常, 秸秆等农残物燃烧的左旋葡聚糖/甘露聚糖比率要高于左旋葡聚糖/半乳聚糖, 树木燃烧的左旋葡聚糖/甘露聚糖比率要低于左旋葡聚糖/半乳聚糖[34]; 不同树木种类之间3种同分异构体的比率也有差异, 比如硬木燃烧的左旋葡聚糖/甘露聚糖比率要高于软木[41]. 结合其他数据资料, 3种同分异构体的比率能够被用于区分植被火燃烧源的种类[33,34,41]. 但需要注意, 甘露聚糖和半乳聚糖占脱水单糖的比例较低, 在远离植被火燃烧源的极地、海岛或深海沉积物中其含量可能会低于检出限[23,42]; 且燃烧状态(焖烧或明火)和燃烧温度也会对3种同分异构体的比率产生影响[30,34]. 此外, 左旋葡聚糖/黑碳比率也能够在一定程度上反映植被燃烧源的变化, 通常高值指示野火燃烧, 低值指示人为秸秆焚烧或薪材燃烧[43,44].

2 不同环境介质中左旋葡聚糖研究进展

近些年, 对气溶胶、冰川雪冰和沉积物等不同环境介质中左旋葡聚糖记录开展了大量的研究工作(图2), 发现除直接反映受植被火燃烧排放影响的基本状况外, 也揭示气溶胶中的左旋葡聚糖记录能够反映事件至季节尺度的植被火燃烧变化特征, 雪冰和沉积物中的左旋葡聚糖记录则能够反映从事件至季节甚至冰期-间冰期尺度的植被火燃烧变化规律, 主要研究进展如下.

2.1 气溶胶中的左旋葡聚糖

左旋葡聚糖主要附着或镶嵌在烟尘颗粒上进行传输[23], 约90%的左旋葡聚糖集中在粒径小于2.5 μm的烟尘颗粒上[40,49,50]. 气溶胶中左旋葡聚糖含量会随采样地点、时间、颗粒物粒径、分析方法等差异而变化[40,41,45,48,49,55,82], 通常在城镇和农村居民生活区左旋葡聚糖含量较高, 高山地区次之, 在海洋和极地地区较低[35,41,47,53,55,58,59](图2).

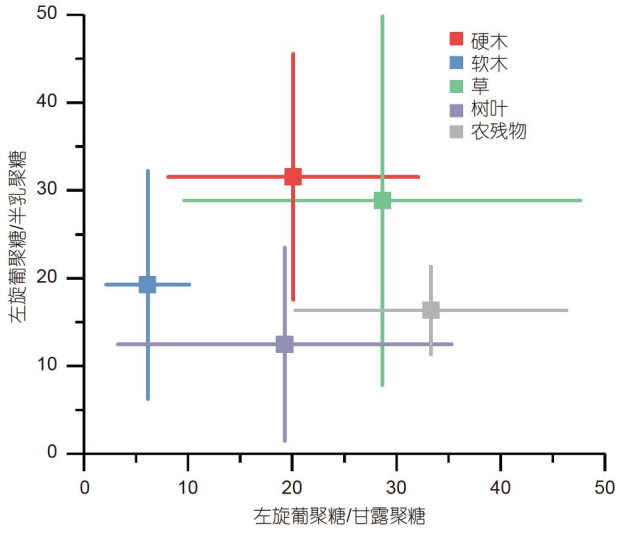

图 1 (网络版彩色)不同植被火燃烧产生的左旋葡聚糖及其同分异构体比率[31,33,37,39,40]

Figure 1 (Color online) Ratios among levoglucosan and its isomers mannosan and galactosan from different fire emissions[31,33,37,39,40]

全球而言，观测和模拟的气溶胶中左旋葡聚糖含量存在明显的空间分布差异. 观测结果显示, 左旋葡聚糖含量高值主要在中纬度地区(图2)，向极地和赤道地区逐渐降低[31,47]. 海洋大气中的左旋葡聚糖含量随到大陆海岸线的距离增加而逐渐降低[47,52,83]. 形成左旋葡聚糖这种空间分布格局的主要原因: 一方面, 在于左旋葡聚糖是一种水溶性成分，在传输过程中会因降水洗脱或烟尘颗粒的重力作用发生沉降[47,68,70]；另一方面, 也因为左旋葡聚糖在大气中会与硝酸根、臭氧、羟基自由基等活性基团发生化学反应而损耗[84]. 根据GEOS-Chem模型估算，大气中约81.5%的左旋葡聚糖因化学反应损耗，约18.4%的左旋葡聚糖沉降到地表, 全球大气中左旋葡聚糖存量约为19 Gg[31].

尽管基于GEOS-Chem模型模拟结果显示左旋葡聚糖的大气寿命平均约为1.8天[31], 但观测证据表明, 由于主要气象参数等的区域差异，左旋葡聚糖的大气寿命通常可在数小时至数十天以上，能确保其进行区域甚至全球尺度的扩散传输. 譬如, 环北极高纬度地区植被火燃烧烟尘能够在数天内被大气环流传输至北极地区并形成“北极烟雾(Arctic smoke)”[54]，采集的气溶胶样品中左旋葡聚糖含量较平常高出约1个数量级. 在南极Mario Zucchelli站，2010年11月至2011年1月观测的气溶胶左旋葡聚糖含量中位数为24.8 pg m^{-3}，但在2010年11月29日因森林火燃烧事件影响，观测到了高达175 pg m^{-3}的极值事件[55].

连续高分辨率的采样观测发现，气溶胶中左旋葡聚糖变化能够捕获植被火燃烧事件[40,55,56], 且可指示火燃烧的月和季节变化特征[41,56,82,85]. 北半球观测的气溶

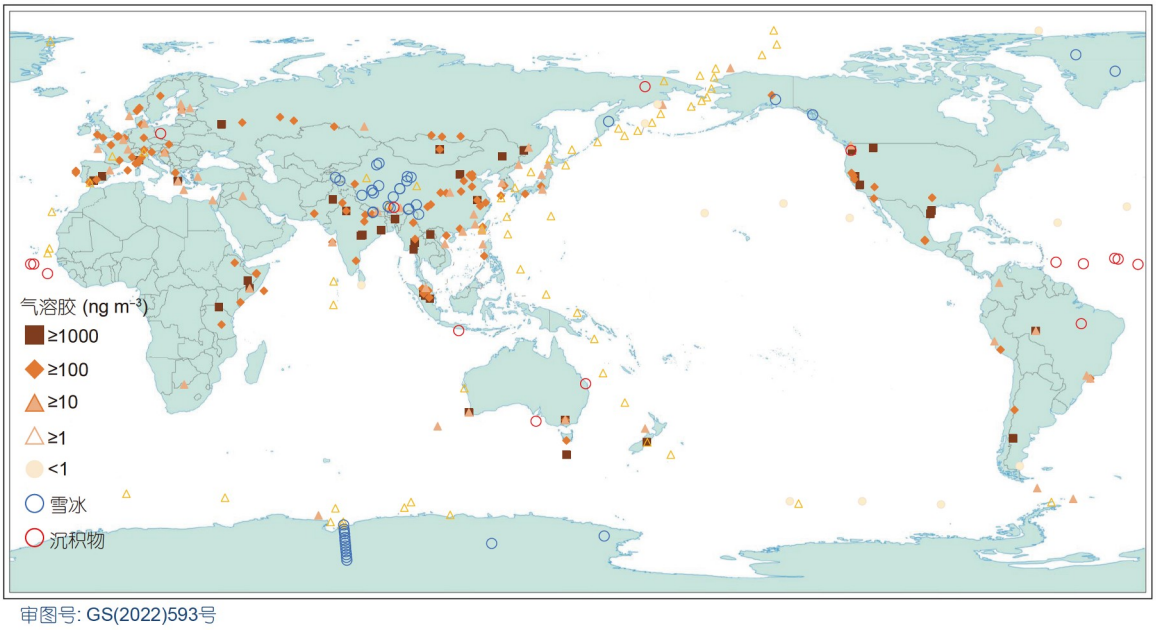

图 2 (网络版彩色)全球气溶胶[23,31,35,36,39,40,45~61]、雪冰[8,24,44,62~76]和沉积物[28,42,46,77~81]中左旋葡聚糖记录的空间分布状况

Figure 2 (Color online) Spatial distribution of levoglucosan in atmospheric aerosol[23,31,35,36,39,40,45–61], glacier snow and ice[8,24,44,62–76], and lake/marine sediments[28,42,46,77–81]

胶样品中左旋葡聚糖记录呈现出明显的秋冬高、春夏低的季节变化规律(图3), 与植被火燃烧季节变化基本一致. 在远离燃烧源的背景地区也有类似变化, 如在太平洋Chichi-jima岛(27°40′N, 142°13′E, 海拔200 m, 图3)气溶胶中, 左旋葡聚糖含量呈现出明显的逐月变化[51]. 在大尺度环流和局地中小尺度天气系统(如山-谷风)的共同作用下[45,87], 植被火燃烧烟尘气溶胶能够通过喜马拉雅山的高山峡谷侵入青藏高原腹地[19], 导致高原内部站点(如纳木错, 海拔4730 m)出现左旋葡聚糖含量峰值[36]; 在高原南部中国科学院珠穆朗玛峰大气与环境综合观测研究站(海拔4276 m), 受喜马拉雅山南坡-恒河谷地森林火灾等影响, 春季(或季风前期)左旋葡聚糖含量要显著高于其他季节, 且与碳质气溶胶和K^+等具有很好的相关性[45].

随海拔高度增加, 烟尘向上传输的热动力逐渐减弱, 导致更高海拔的自由对流层大气中左旋葡聚糖含量急剧降低. 比如, 关中盆地的西安[48](34.27°N, 108.90°E, 海拔~430 m)气溶胶中左旋葡聚糖含量大约是华山[49](34°29′N, 110°05′E, 海拔2060 m)的9倍; 欧洲匈牙利K-Puszta(46°58′N, 19°35′E, 海拔136 m)农村站点左旋葡聚糖含量大约是奥地利Sonnblick(47°03′N, 12°57′E, 海拔3106 m)高山站点的40倍[53]. 但森林火灾等大规模植被火燃烧事件会释放大量的热量, 在其强热对流动力作用下烟尘气溶胶能够被抬升至对流层顶部至平流层底部的高度, 最终在高空大气环流作用下进行远源传输[13,14,88], 这可能也是极地冰盖和高海拔山地冰川覆盖区大气中左旋葡聚糖记录的主要传输方式. 在全球极高海拔山地的观测资料显示, 这些地区的左旋葡聚糖含量比火燃烧排放严重的平原地区低2~3个数量级[36,45,53], 与远离植被火燃烧排放源的海洋岛屿和极地地区大气中的含量相当, 基本能够代表区域背景条件[35].

2.2 水体中的左旋葡聚糖

左旋葡聚糖是一种完全水溶性的脱水单糖成分[23,30], 黏附在烟尘颗粒表面上会使得其吸湿性增强[30], 可作为云凝结核并有利于云滴吸湿性增长[89], 在水汽充足的情况下会有助于降水(包括降雨和降雪等)形成. 在北京冬季雾霾发生时, 会在气溶胶中观测到极高的左旋葡聚糖含量[41,56], 但降水事件发生后, 气溶胶中的左旋葡聚糖含量会降低2~3个数量级, 而降水样品中则会检测出极高的左旋葡聚糖含量[90]; 在赤道附近海洋采集的气溶胶样品中, 左旋葡聚糖含量也会随降水而急剧降低[47]. 这些证据表明, 降水洗脱可能是左旋葡聚糖从大气中被清除的主要方式之一. 比如, 在美国Wilmington的观测结果表明, 来自植被火燃烧源区陆地气团降水中的左旋葡聚糖含量要高于来自海洋方向气团降水[91]. 青藏高原拉萨降水样品中左旋葡聚糖含

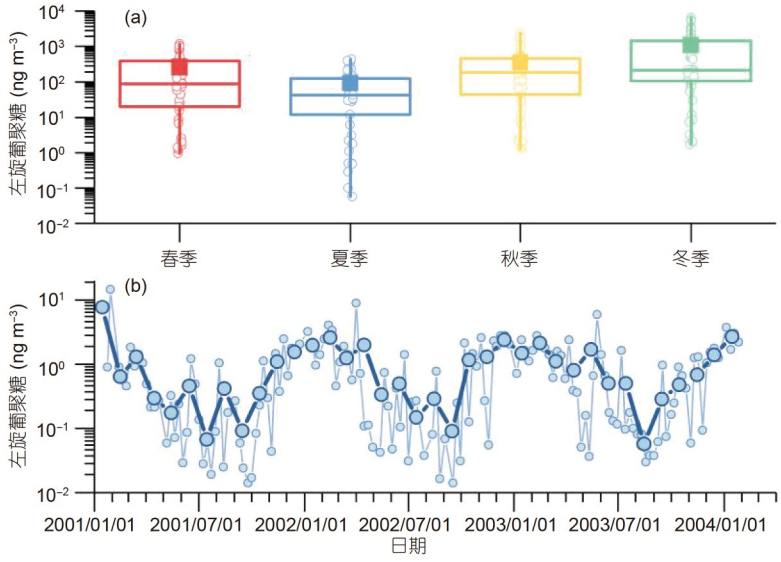

图 3 (网络版彩色)北半球大陆站点[31,35,39~41,47~49,51~53,56,57,60,83,85,86](a)与太平洋Chichi-jima岛站点2001年1月至2004年2月连续采样[51]气溶胶左旋葡聚糖的变化(b). 细点线表示逐次数据, 粗点线表示逐月平均

Figure 3 (Color online) Variations of levoglucosan in Northern Hemisphere continental sites[31,35,39–41,47–49,51–53,56,57,60,83,85,86] (a) and Chichi-jima Island in the Pacific during Jan. 2001–Feb. 2004[51] (b). The fine dot-line indicates successive data and thick dot-line indicates monthly average data

量要高于高原腹地高海拔冰川覆盖区[35].

在赤道大西洋地区同一经纬度采集的不同深度海水样品中, 左旋葡聚糖含量的垂直差异并不明显, 表明在海水中左旋葡聚糖降解并不明显[81]. 在实验室条件下, 将同一批左旋葡聚糖水溶液样品(ng g^{-1}浓度水平)反复冻融, 发现用聚四氟乙烯等塑料样品瓶盛放的样品中左旋葡聚糖含量差异非常小, 表明水体中左旋葡聚糖降解微弱[25,92]. 但当前对包括降水、河水、湖水等天然水体中左旋葡聚糖的研究非常稀少, 而这些水体是连接大气与地表沉积物的纽带, 是理解地表环境介质中左旋葡聚糖记录的关键, 未来的工作需要进一步加强观测研究.

2.3 雪冰中的左旋葡聚糖

附着在烟尘颗粒上的左旋葡聚糖能够被大气环流携带传输至极地和中低纬度高海拔冰川覆盖区, 随降雪进入冰川雪冰层并成为雪冰化学的重要成分之一[17,24]. 冰川积累区的气候环境主要受大尺度环流影响, 通常能够反映区域乃至全球尺度的气候环境过程, 局地排放源的贡献微弱[64,67,70]. 此外, 冰川积累区几乎不会受到人类活动的扰动[70]. 因此, 雪冰层中的左旋葡聚糖记录能够为理解区域乃至全球植被火燃烧变化提供关键科学依据[8]. 全球雪冰中左旋葡聚糖记录样品点如图2所示.

中低纬度山地冰川雪冰中左旋葡聚糖含量在1 ng g^{-1}数量级[24,63,65,66,68], 比南北极地区要高1~2个数量级[64,67,72,73]. 位于高原南部希夏邦马峰南坡尼泊尔的雅拉冰川, 植被火燃烧烟尘能够被山谷风携带传输至高海拔冰川覆盖区, 使雅拉冰川雪冰中左旋葡聚糖含量较之希夏邦马峰北坡的达索普冰川高2~3个数量级[68]. 青藏高原边缘地区冰川雪冰中左旋葡聚糖含量要比高原腹地地区的冰川大约高1个数量级[35,65]. 通过大气模型将高原腹地冰川雪冰中左旋葡聚糖转换为大气中左旋葡聚糖含量, 大致在10 ng m^{-3}数量级, 与海岛和极地地区含量相当, 表明高原腹地地区拥有洁净的环境条件[35]. 在南极地区也观测到了边缘比腹地雪冰中左旋葡聚糖含量要高的现象[67].

冰川表面的左旋葡聚糖记录信号会随着雪冰的老化和成冰过程发生变化[64,70]. 在山地冰川消融区, 左旋葡聚糖会被冰川融水带走[71]. 在冰川积累区, 粒雪颗粒表面融化时, 左旋葡聚糖会随融水沿着粒雪颗粒间的空隙下渗. 在一定深度当温度低于冰点时发生冻结, 随着粒雪间空隙封闭而出现在冻结冰层处富集的现象[70](如图4所示, 措普沟冰芯中左旋葡聚糖和黑碳在春季形成的污化层附近富集), 因此产生的淋溶过程在一定程度上会改变左旋葡聚糖在冰川表面的原始沉积信号. 但积累区的淋溶过程通常并不会穿透前一年形成的附加冰层, 山地冰川积累区左旋葡聚糖记录也通常能够反映年际尺度甚至季节尺度的植被火燃烧变化信号[70,71]. 为了减小沉积后过程的可能影响, 在利用山地冰芯开展左旋葡聚糖记录研究时, 需要尽量在高海拔积累区采集样品. 在南北极冰盖积累区雪冰几乎不会融化, 左旋葡聚糖记录能够揭示植被火燃烧的季节变化信号, 甚至能够捕获极强的植被火燃烧事件[64]. 但南北极冰盖的成冰作用时间长, 粒雪颗粒间空隙中包含硝基、羟基自由基等活性基团可能会引起左旋葡聚糖氧化降解[64,67,93], 但其影响有待进一步研究确认. 这些过程也造成了左旋葡聚糖与传统指标K^+、草酸根和黑碳等记录的差异[63,64,70], 尽管植被火燃烧并非这些成分的主要物质来源, 在极地地区它们通常也被用作指示植被火燃烧的变化[17,73].

将现代冰芯记录与卫星遥感资料对比发现(图5), 左旋葡聚糖记录能够很好地反映年际尺度的植被火燃烧变化[44], 冰芯中左旋葡聚糖含量峰值也能在一定程度上反映植被火燃烧事件[63,66,73], 为利用冰芯左旋葡聚糖记录研究植被火燃烧变化历史提供了理论基础[63,69]. 如利用青藏高原藏色岗日冰芯左旋葡聚糖记录揭示了喜马拉雅山沿线地区在21世纪初期森林火灾等火燃烧快速增强[44].

南极Taylor Dome冰芯和格陵兰NEEM冰芯左旋葡聚糖记录都揭示了全新世以来植被火燃烧逐渐增强的趋势[62,72]; 火燃烧在大约2~3 ka BP达到峰值, 随后逐渐减弱, 这与炭屑记录反演的火燃烧变化是基本一致的[72], 可能与同期全球人类用火开垦荒地等活动增强有关[1,72,94]; 而NEEM冰芯中左旋葡聚糖极值事件在近2000年也更频繁出现[73]. 在南极Dome C冰芯中, 冰期样品中左旋葡聚糖含量高于间冰期样品[75], 可能反映了南半球冰期-间冰期的植被火燃烧变化规律. 但南北极地区远离植被火燃烧源, 冰芯样品中左旋葡聚糖含量比青藏高原为代表的中低纬度地区低2~3个数量级[24,62,72,73], 且不连续取样可能会造成一些记录信息丢失[8]. 近年来, 借助原子阱单原子检测定年方法, 发现青藏高原古里雅冰帽等年代可超过74 ka BP[95], 在古里雅冰帽海拔6700 m处获取的冰芯底部样品中也检测到了

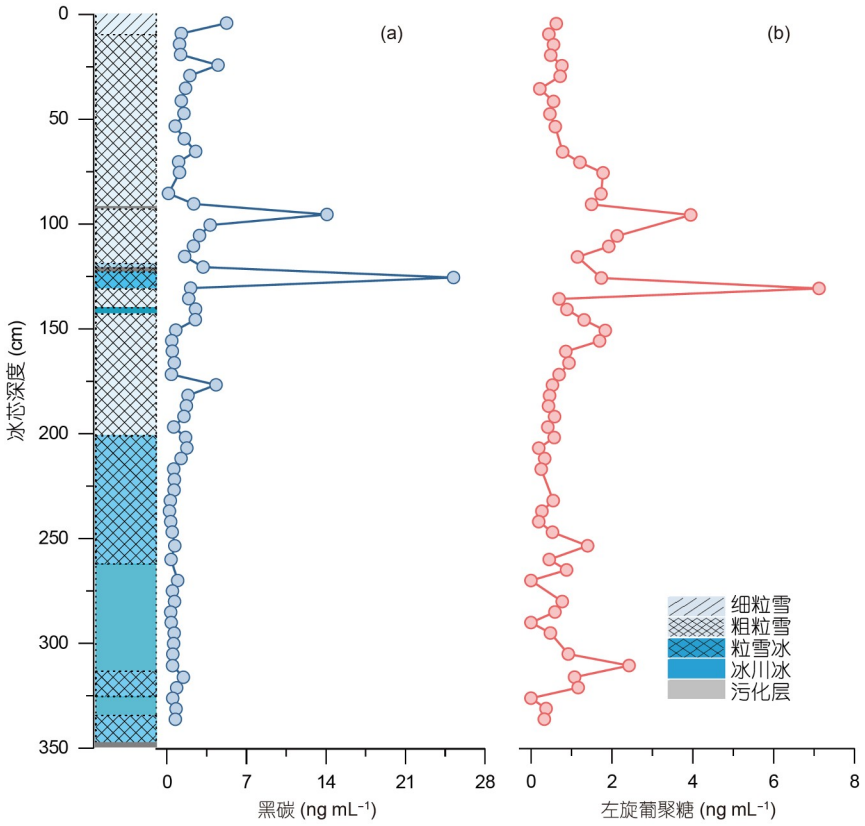

图 4 (网络版彩色)青藏高原东南部措普沟冰芯的特征描述与黑碳(a)和左旋葡聚糖(b)记录[70]
Figure 4 (Color online) Visual stratigraphy of ice core characteristics of Cuopugou ice core and its variation of black carbon (a) and levoglucosan (b) concentrations[70]

较高的左旋葡聚糖含量(约2 ng g^{-1}，相关研究未发表)，有望为理解亚洲等中低纬度地区冰期-间冰期尺度的植被火燃烧变化提供高分辨率证据.

2.4 沉积物中的左旋葡聚糖

湖泊、黄土和海洋沉积物中炭屑与黑碳记录是当前开展植被火燃烧变化历史研究的主要手段[1,5,21,22,94]. 烟尘气溶胶上吸附或镶嵌的左旋葡聚糖在降水洗脱和干沉降作用下，能够进入湖泊和海洋水体[42,81]；此外，河流也可能会携带流域内植被火燃烧产生的左旋葡聚糖进入湖泊和海洋水体[81,96]. 因此，湖泊和海洋沉积物中的左旋葡聚糖记录能够比炭屑记录反映更大尺度范围的植被火燃烧变化[80]. 左旋葡聚糖在水-沉积物界面上可能会因为暴露于沉积物表面的氧气中而发生降解，但随着沉积过程左旋葡聚糖最终会被包裹进入沉积物中并处于缺氧环境而逐渐趋于稳定状态[81]. 尽管目前对湖泊和海洋沉积物中左旋葡聚糖记录的研究稀少，但基本明确了左旋葡聚糖记录能够被用于重建植被火燃烧变化历史[23,97].

湖泊沉积物中的左旋葡聚糖记录与传统植被火燃烧指标炭屑或黑碳记录等(图6)具有很好的一致性[78,97]，且同时出现的炭屑和左旋葡聚糖记录峰值能够指示极强植被火燃烧事件的影响[97]. 在青藏高原帕如措(Paru lake，海拔4850 m)沉积物中左旋葡聚糖及其同分异构体含量在μg g^{-1}水平，比高原冰川雪冰中的含量高了约2~3个数量级，可能指示了湖泊沉积物较低的沉积速率引起左旋葡聚糖富集[79]. 在南美Cariaco Trench约270 ka BP的沉积物中和俄罗斯西伯利亚El'gygytgyn约430 ka BP沉积物中都检测到了较强的左旋葡聚糖信号[46,97]. 但左旋葡聚糖与炭屑等记录也存在相位差异(图6)，可能与两者的物质来源、沉积后的地球化学过程、反映的植被火燃烧空间尺度差异等有关[78,97]，需要更多研究工作进一步明确. 这些证据表明，在湖泊沉积物封闭的环境条件下左旋葡聚糖能够长期存在，有望为揭示和理解冰期-间冰期尺度的植被火燃烧变化提供新的代用指标与关键证据.

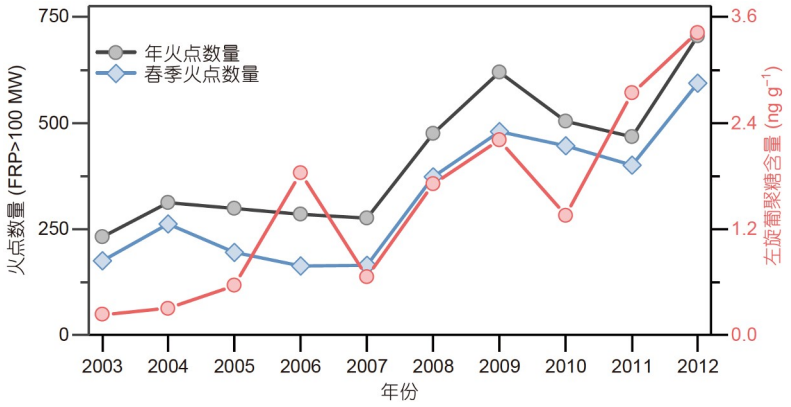

图 5 (网络版彩色)青藏高原藏色岗日冰芯中2003~2012年左旋葡聚糖含量变化与MODIS卫星观测的上风向地区火点数量变化[44,69]
Figure 5 (Color online) Annually-resolved levoglucosan changes in the Zangsegangri ice core on the Tibetan Plateau and MODIS fire counts in the windward direction during 2003–2012[44,69]

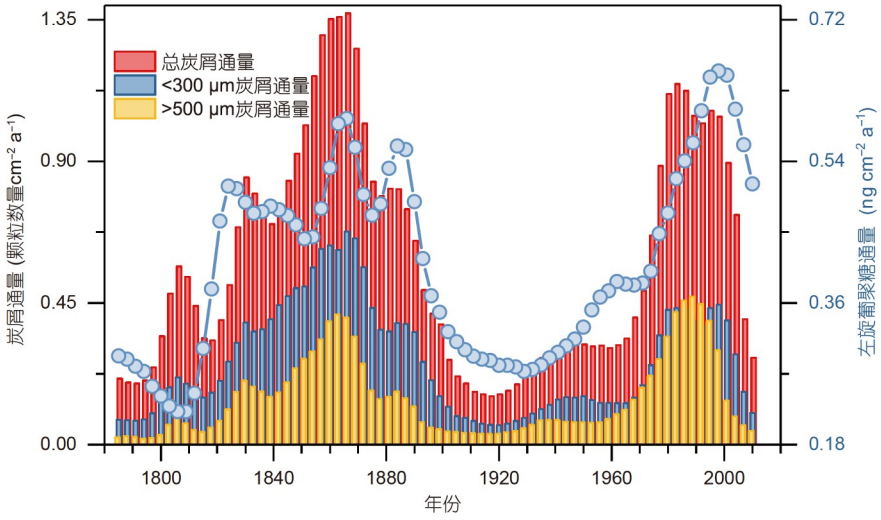

图 6 (网络版彩色)波兰Czechowskie湖泊沉积物中炭屑与左旋葡聚糖的变化[78]
Figure 6 (Color online) Variations of levoglucosan and charcoal in lake Czechowskie, Poland[78]

海洋沉积岩芯中左旋葡聚糖记录能够反映冰期-间冰期尺度上植被火燃烧变化与气候和人类活动的相互作用关系. 非洲西海岸Guinea湾钻取的深海沉积岩芯GeoB9528-3中记录了192 ka BP以来的左旋葡聚糖变化, 揭示了MIS-3阶段因C3植物增加和人类活动增强共同导致的植被火燃烧增强[42]. 澳大利亚东南部Lacepede Shelf地区MD03-2607沉积岩芯记录的130 ka BP以来左旋葡聚糖变化[77,98]与炭屑记录存在较大差异, 如在125~75 ka BP炭屑处于较高水平, 但左旋葡聚糖处于低水平[77]; 在20 ka BP前后的末次冰期冰盛期左旋葡聚糖高水平时炭屑记录处于较低水平. 造成这种差异的可能原因在于海洋沉积物中的炭屑主要是靠河流输送, 而左旋葡聚糖也受到气溶胶颗粒携带传输输入的影响所致[77,98]. 但对海洋沉积物中左旋葡聚糖记录研究处于起步阶段, 有待更多的工作去明确.

3 总结与展望

左旋葡聚糖记录与植被火燃烧变化研究在近年来越来越受到关注. 当前已获得的研究认识表明, 地表不同环境介质中的左旋葡聚糖记录均能够在一定程度上指示火燃烧变化规律与特征. 但要更全面科学地理解左旋葡聚糖指示植被火燃烧的代表性和可靠性, 以下3个问题要特别关注.

第一, 左旋葡聚糖在环境介质中的稳定性是首要

问题. 左旋葡聚糖在不同气象条件大气中的稳定性、在大气-水界面的稳定性、在水-沉积物界面的稳定性等问题直接关系到左旋葡聚糖作为植被火燃烧代用指标的可靠性[8], 亟需观测和模拟研究来证实. 比如, 当前对大气中左旋葡聚糖寿命的观测和模拟结果差别非常大[31,52,54,84]; 除受淋溶作用影响, 在粒雪颗粒间隙中的左旋葡聚糖也可能受到羟基自由基等活性基团的氧化降解; 粒雪颗粒间隙的雪冰融水和沉积物表面的微生物代谢对左旋葡聚糖的可能消耗等问题目前都没有清晰的认识, 但又很可能会影响到左旋葡聚糖记录的解析. 另一方面, 尽管左旋葡聚糖来源单一, 但其记录也受到了很多因素影响[54,70,81], 只有将左旋葡聚糖记录与炭屑、黑碳、小分子有机酸等多指标结合起来对比研究, 才有望得到更系统的科学认识[8,17,24,42].

第二, 尽快获取中低纬度冰芯和湖芯高分辨率的左旋葡聚糖记录. 当前对全球火燃烧变化的认识主要是利用沉积物炭屑记录得到的[1,94], 但在亚洲地区因人类活动扰动等原因, 导致沉积物炭屑记录稀少且分辨率较粗[94]. 利用冰芯记录能够为理解全球植被火燃烧变化与人类活动的相互作用关系提供关键信息, 尤其是可能提供近千年来年际分辨率的植被火燃烧变化记录[8], 有望为理解中低纬度区域的火燃烧变化、温室气体和碳排放问题等提供重要的科学依据. 全球变化引起高海拔冰川覆盖区快速升温, 导致冰川物质平衡线升高, 冰川加速消融[99,100], 科学家只能到更高海拔积累区获取冰芯[8,101]. 高海拔地区湖泊沉积物左旋葡聚糖记录也可能反映区域尺度的植被火燃烧变化[79], 且冰川末端湖泊沉积速率大、沉积物分辨率较高, 如能与冰芯记录对比研究, 有望提供更可靠的证据. 此外, 南极蓝冰[102]也有望为理解100万年前植被火燃烧与温室气体变化提供契机.

第三, 从地球系统科学角度解析左旋葡聚糖记录和理解植被火燃烧变化. 作为一种环境代用指标, 左旋葡聚糖在地表环境介质中广泛存在, 这些环境介质涉及生物圈、大气圈、水圈、冰冻圈与岩石圈(主要是沉积物)等地表圈层, 并在这些圈层间迁移(主要过程如图7所示). 左旋葡聚糖在不同圈层环境介质中/间的迁移能够直接影响到其记录解析. 在考虑自然过程和人类活动影响的情况下, 从地表多圈层相互作用角度开展工作有利于理解影响左旋葡聚糖记录的地球化学过程, 也有利于认识左旋葡聚糖对植被火燃烧变化的指示意义, 并进一步为深化认识全球变化下植被火燃烧-气候系统及人类社会之间的相互作用提供全新的代用指标和有力的科学支撑.

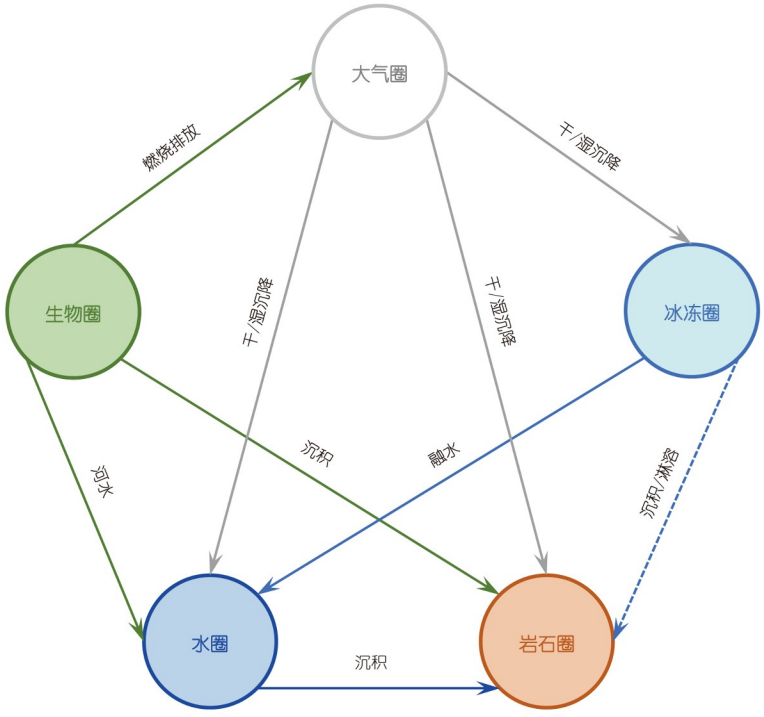

图 7 (网络版彩色)左旋葡聚糖在地表圈层主要环境要素之间的迁移过程概念图
Figure 7 (Color online) Concept map for the transport process of levoglucosan among various environmental media in earth surfaces

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Summary for “环境介质中左旋葡聚糖记录与植被火燃烧变化研究进展”

Progress of levoglucosan records and vegetation fire changes in environmental media

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Vegetation fire, also called biomass burning, wildfire, landscape fire, bushfire, forest fire, scrub fire, crop residue burning, peat bog fire, savanna fire and grass fire, are spontaneous combustion of plants in a natural setting. Vegetation fires began soon after the appearance of terrestrial plants in the Silurian about 420 million years ago. The regime of vegetation fire has varied with long-term changes in global climate and shorter-term regional changes in climate and vegetation since then, and human beings have altered fire activity since the mid-Holocene, especially in recent years. Vegetation fire affects vegetation distribution, ecological structure, biogeochemical and hydrologic cycles, geophysical processes, and the climate system at local to global scales. Vegetation fire is one of the largest sources of trace gases and aerosols in the Earth's atmosphere. It contributes more than half of black carbon and about 80% of primary organic aerosol worldwide. Besides, smoke aerosol from vegetation fire is composed of hundreds of chemical components, and many of which (e.g., polycyclic aromatic hydrocarbons) are known to be harmful to human health. Fire smoke causes more than 600000 premature deaths annually worldwide. Therefore, understanding the spatial-temporal changes of vegetation fire is of great importance. Using some specific biomarkers for tracing changes and emissions of vegetation fire has become a research focus in recent years.

Among various chemical components, anhydro-sugars are mainly emitted by pyrolysis of cellulose and hemicellulose when burning temperature exceeds 300°C, whereas the contribution of fossil fuel emissions seems to be negligible. Levoglucosan accounts for more than 90% of anhydro-sugars in the nature. Levoglucosan has been reported with a lifetime longer than ten days under most atmospheric conditions, and thus could be transported far from the fire sources. The annual total levoglucosan emission is estimated at about 3.8 Tg (million ton) per year worldwide, however, when atmospheric degradation is considered, the atmospheric budget of levoglucosan is only about 1.9 Gg (kiloton) as calculated by the GEOS-Chem global 3-D chemical transport model. Eventually, levoglucosan is scavenged out the atmosphere to be deposited on earth surfaces by precipitation or gravitational processes. Its presence has been detected in various environmental medias including atmospheric aerosols, precipitation, lake/sea water, snowfall, glacier snow/ice, lake/marine sediments. High levoglucosan concentration/flux is usually found in middle and low latitudes where intense fire sources are nearby. In comparison, extreme low concentration/flux are found on highmountains, polar regions and marine sites where levoglucosan can only arrive by long distance transportation. Levoglucosan has been widely used as a biomarker for tracing fire emissions ranging from event to glacial-inter glacial timescales. For example, levoglucosan has been detected in lake sediments older than 430 ka years before present under anoxic environmental conditions. This work summarized the recent progress of levoglucosan records and vegetation fire changes in various environmental media. Levoglucosan in atmospheric aerosols can reflect fire emissions from event to seasonal scales, and levoglucosan records in glacial ice and lake/marine sediments can reveal fire evolution from seasonal to glacial-interglacial timescales. Overall, the current knowledge supports that levoglucosan should be an ideal biomarker for tracing vegetation fire changes on Earth's surface. However, more evidences are needed in the near future to better understand its stability, interpret its records in ice core and sediments, as well as its relation with other proxies.

levoglucosan, vegetation fire, aerosol, water, snow and ice, sediment

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