火星表面含水矿物探测进展

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摘 要：火星表面含水矿物类型识别和空间分布特征研究对圈定火星表面生命活动有利区域和探索可能存在的火星生命形式具有重要科学意义。本文总结了20世纪90年代以来火星表面含水矿物的探测进展，从火星轨道器光谱仪遥感探测、着陆器和巡视器就位探测两方面介绍了矿物探测使用的数据源，重点阐述了目前火星表面已经探测到的各类含水硅酸盐矿物、硫酸盐矿物、碳酸盐矿物、氯盐及高氯酸盐矿物等含水矿物的光谱特征、矿物具体类别及分布特征，分析了火星表面含水矿物定量反演的主要方法与地质意义。最后从比较行星学角度倡议开展地球和火星含水矿物形成环境和形成过程的类比研究。

关键词：火星表面，含水矿物，遥感探测，就位探测，定量反演，比较行星学

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1 引言

火星作为太阳系八大行星中与地球最为相似的星球，成为各航天大国深空探测任务的最主要目标之一。1960年，苏联发射的首颗火星探测器Mars 1960A，正式拉开了人类探测火星的序幕。此后，美国、欧洲空间局、印度等国家和组织相继实施了一系列的火星探测任务，科学目标涉及火星演化历史、火星磁场、火星地质构造与地貌、火星古气候古地理环境等方面，获取了大量的科学数据和成果。

火星表面存在撞击坑和大型撞击盆地、盾形火山、风成沙丘、极区极冠、峡谷系统、干涸河床和沟渠等多种地貌。广泛发育的干涸河床、三角洲、冲积扇和沟渠等反映了火星表面曾经存在液态水环境，这些流水地貌记录了火星表面不断被侵蚀改造的过程。在地球上，水环境的存在往往与生命活动密切相关，因此，各类火星探测任务的重点目标之一总是包括探寻和追踪水曾经或目前在火星表面不同的存在形式和证据(Hubbard等，2002)，如极冠永久水冰、地下水冰、地表短时液态水以及以不同形式存在于矿物中的水。

在许多矿物的形成过程中，水都发挥了重要作用，它对矿物的物理化学性质有显著影响。水合或水化矿物(hydrous/hydrated minerals)是指水以吸附水、结晶水、结构水3种基本类型存在于矿物晶体结构中而形成的矿物。火星表面常见的水合或水化矿物是含水硅酸盐类粘土矿物，它们通常是水参与条件下热液蚀变和变质的产物，能够指示粘土矿物形成时的温压条件和揭示古气候环境演变过程(汤艳杰 等，2002)。蒸发盐矿物(evaporites)形成于有水环境，是水溶液蒸发干涸后水体中溶解的成盐离子析出的产物，其矿物晶体结构中可能含水，也可能不含水。它反映了矿物沉积时水活动的线索，意味着火星表面曾被水侵蚀(郑绵平 等，2014；王洪浩 等，2015)。本文讨论的这两类矿物的形成都需要水的参与，因此将它们也统称为“含水矿物”(aqueous minerals)(JHU/APL，2016)。

火星表面含水矿物与水溶液活动密切相关，

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是火星表面曾经存在水环境的最明显和最直接的地质证据。水溶液环境具备孕育和维持生命的基本条件，含水矿物的类别与丰度提供了这些矿物形成时水溶液的温度、盐度、酸碱度等信息，且它们具有保存古老生命遗迹的能力，因此含水矿物研究逐渐成为火星地质研究的热点问题，它们的富集区是搜寻可能的火星古老生命迹象、开展火星表面古气候古环境研究等工作的良好候选地区。研究人员在开展火星古地理古气候研究以及搜寻火星早期可能存在的生命证据时，重点关注火星表面发现含水矿物的地区。因此火星表面各种类型含水矿物的识别、空间分布和地质环境研究对圈定火星表面生命活动有利区域和探索可能存在的火星生命形式具有重要科学意义。本文从火星表面矿物探测数据源、含水矿物识别方法与成果、含水矿物定量反演方法与成果3个方面对火星表面含水矿物探测的最新科研成果进行综述，并在此基础上探讨未来的研究方向，希望为中国火星遥感探测与火星科学研究以及2020年将要实施的火星探测任务提供参考。

2 火星表面矿物探测数据源

火星表面矿物种类识别和岩性划分是研究火星地质演化历史的基础工作。火星表面矿物探测既可以利用太空望远镜数据开展分析工作(Bell 等，1997；Elmahboub和Yankey，2005)，也可通过火星陨石开展识别研究(McSween，1985；Bridges和Grady，2000)，但目前主要还是基于轨道器搭载的光谱仪以及巡视器和着陆器携带的科学仪器开展火星表面矿物的遥感探测与就位探测。遥感探测光谱仪主要是利用矿物在热红外光谱范围内的发射光谱特征和矿物在可见近红外光谱范围内的反射谱带特征探测和识别矿物。就位探测巡视器和着陆器主要通过其搭载的科学仪器对火星表面土壤、矿物、岩石等开展详细的成分鉴定、含量检测等分析工作。下文将简要介绍20世纪90年代以来搭载于轨道器进行遥感探测的光谱仪，以及搭载各种科学仪器开展就位探测的着陆器和巡视器。

2.1 火星遥感探测轨道器光谱仪

2.1.1 热辐射光谱仪

热辐射光谱仪TES (Thermal Emission Spectrometer)搭载于1996年11月美国发射的火星全球勘探者MGS(Mars Global Surveyor)轨道器(表1)。它通过测量火星表面和大气辐射研究：(1)火星表面矿物、岩石以及冰的成分；(2)火星大气层温度与动力学特征；(3)火星大气气溶胶与云的性质；(4)火星极区性质；(5)火星表面物质热物理性质(Christensen 等，2001)。TES探测结果使人们对火星地质概况与火星大气层等有了较为全面的认识(Bandfield 等，2000；Mellon 等，2000；Smith 等，2002；Smith，2004)。

表 1 20世纪90年代以来火星表面矿物遥感探测主要仪器关键技术指标

Table 1 Key specifications of major orbital instruments for mineral detection on Martian surface since 1990s

光谱仪名称	轨道器名称	发射时间	空间分辨率	光谱分辨率	波长范围/μm	波段数
TES	MGS	1996	约3×6 km	10 cm^{-1}或20 cm^{-1}	6—50	148或296
THEMIS*	MO	2001	100 m	–	6.7—14.8	10
OMEGA	MEX	2003	0.3—4.8 km	7—20 nm	0.36—5.1	352
CRISM	MRO	2005	18—200 m	6.55 nm	0.36—3.92	544或72

注：*这里指热红外多波段数据。

2.1.2 热辐射成像系统

热辐射成像系统THEMIS(Thermal Emission Imaging System)搭载于2001年4月发射的火星奥德赛MO(Mars Odyssey)轨道器(表1)。它的主要科学任务包括：(1)测定与热液或水环境相关的火星表面局部沉积物的矿物和矿石成分；(2)搜寻蕴涵地下活跃热液系统的火星表面热异常区；(3)利用形态和热物理性质研究小尺度地质过程与着陆区特征；(4)研究各个季节火星极盖的时空变化过程(Christensen 等，2004)。THEMIS不仅获得了高分辨率的火星全球影像图(Edwards 等，2011)，还使人们对火星地表的物理特征及热性质等有了更为深入的了解(Christensen 等，2003, 2005；Titus

等，2003；Bandfield 等，2004；Fergason 等，2006；Edwards 等，2009)。

2.1.3 可见光及红外矿物填图光谱仪

可见光及红外矿物填图光谱仪OMEGA (Observatoire pour la Minéralogie, l’Eau, les Glaces et l’Activité)搭载于2003年6月欧洲空间局发射的火星快车(Mars Express, MEX)轨道器(表1)，它主要用于：(1)探测和识别火星表面主要地质单元上岩石和矿物的成分；(2)研究火星南北极冠的水冰、干冰、层状沉积物和季节性霜冻的空间演化过程；(3)监测和反演火星大气总气压、气溶胶含量、大气垂直温度分布等(Bibring 等，2004b)。OMEGA数据广泛应用于火星表面矿物填图(Bibring 等，2005；Poulet 等，2006, 2007；Ody 等，2012, 2013)、火星极冠水冰和干冰季节性变化监测(Bibring 等，2004a；Langevin 等，2005b)、火星大气组分分析(Melchiorri 等，2007；Bertaux 等，2012)、火星大气气溶胶光学厚度反演(Vincendon 等，2007)等研究。

2.1.4 紧凑型火星侦察成像光谱仪

紧凑型火星侦察成像光谱仪CRISM (Compact Reconnaissance Imaging Spectrometer for Mars)搭载于2005年8月美国发射的火星侦察轨道器MRO (Mars Reconnaissance Orbiter)(表1)。CRISM主要用于：(1)绘制火星表面全球矿物分布图以推断形成火星地壳的地质过程；(2)在高光谱和高空间分辨率模式下精细识别与绘制火星表面重点区域(主要为含水矿物特征明显地区)矿物成分与分布模式来研究火星表面曾经的水环境特性；(3)观测火星大气成分(如水汽，尘埃)空间与季节变化特性以更加了解火星气候和季节(Murchie 等，2007)。CRISM成功在火星表面识别出各种粘土矿物、硫酸盐矿物和碳酸盐等矿物(Bishop 等，2008；Ehlmann 等，2008；Mustard 等，2008；Ehlmann 等，2009；Lichtenberg 等，2010；Michalski和Niles，2010；Wray 等，2010；Wendt 等，2011；Carter 等，2013)，部分探测成果还得到了勇气号、机遇号以及好奇号巡视器就位分析结果的实地验证(Morris 等，2010；Squyres和Arvidson，2013；Bridges 等，2015)。CRISM还用于火星大气和极冠的探测(Brown 等，2010a；Smith 等，2013)。

2.2 火星就位探测着陆器和巡视器

2.2.1 火星探路者着陆器和索杰娜巡视器

火星探路者着陆器MPF (Mars Pathfinder) (Golombek，1997)于1997年7月4日在火星表面Ares峡谷着陆(Golombek 等，1999)(图1和表2)。它携带的索杰娜(Sojourner)火星车是人类送往火星的第一部巡视器，其装备的α粒子X射线谱仪APXS (Alpha Particle X-ray Spectrometer)主要用于分析火星岩石及土壤中的元素及其丰度。

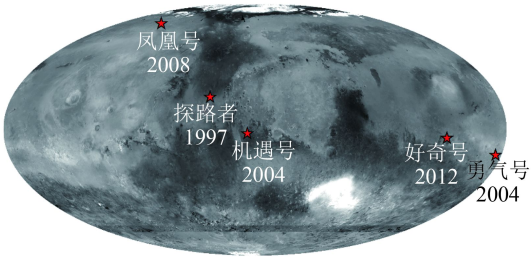

图 1 20世纪90年代以来成功登陆火星的着陆器和巡视器及其着陆时间(底图为MOC影像)

Fig. 1 Landers and rovers that successfully landed on the Martian surface since 1990s overlain on MOC image

表 2 20世纪90年代以来成功登陆火星表面的着陆器和巡视器

Table 2 Landers and rovers that successfully landed on the Martian surface since 1990s

火星车	登陆时间	登陆地点	矿物就位探测主要相关仪器
火星探路者着陆器和索杰娜巡视器	1997年7月4日	Ares峡谷	α粒子X射线谱仪APXS
勇气号巡视器 机遇号巡视器	2004年1月3日 2004年1月25日	Gusev撞击坑 Meridiani平原	α粒子X射线谱仪APXS 微型热辐射光谱仪Mini-TES 穆斯堡尔谱仪MB
凤凰号着陆器	2008年5月25日	北极冰原地区	热量及挥发气体分析仪TEGA 显微镜及电化学与传导率分析仪MECA
好奇号巡视器	2012年8月6日	Gale撞击坑	α粒子X射线谱仪APXS 化学与矿物学分析仪CheMin 火星样本分析仪SAM 化学与成像仪器ChemCam

2.2.2 火星探测巡视器

火星探测巡视器任务MER (Mars Exploration Rover)(Crisp 等，2003)由勇气号(Spirit)与机遇号(Opportunity)巡视器组成，勇气号于2004年1月3日在火星南半球的Gusev撞击坑着陆(Arvidson 等，2006)，机遇号于2004年1月25日在火星表面Meridiani平原(Squyres 等，2006)着陆(图1和表2)。它们携带相同的科学载荷，除携带APXS外，穆斯堡尔谱仪MB (Mössbauer Spectrometer)用于近距离分析岩石和土壤中的含铁矿物；微型热辐射光谱仪Mini-TES (Miniature Thermal Emission Spectrometer)用于近距离识别岩石和土壤并确定它们的成因。

2.2.3 凤凰号着陆器

凤凰号着陆器(Phoenix)(Shotwell，2005)于2008年5月25日成功着陆在靠近火星北极的冰原地区(Hoffman 等，2008)(图1和表2)。它搭载了多种科学探测仪器，热量及挥发气体分析仪TEGA (Thermal and Evolved-Gas Analyzer)用于加热火星土壤样品，并测量样本中水蒸气、二氧化碳及挥发性有机物(如甲烷)随温度上升而产生的变化；显微镜及电化学与传导率分析仪MECA (Microscopy, Electrochemical, and Conductivity Analyzer)用于综合分析火星土壤样品的酸碱度、水溶性离子(如镁、钠阳离子、氧化物、溴化物、硫酸盐阴离子)的化学特性、电导率和热导率。

2.2.4 好奇号巡视器

好奇号巡视器(Curiosity)(Grotzinger 等，2012)于2012年8月6日在火星赤道南部的Gale撞击坑着陆(Vasavada 等，2014)(图1和表2)。除装备APXS外，化学与矿物学分析仪CheMin (Chemistry and Mineralogy)用于确定火星上矿物的类型和数量；火星样本分析仪SAM (Sample Analysis at Mars)负责搜寻构成生命的要素—碳化合物和搜寻与地球上的生命有关的其他元素，例如氢、氧和氮；化学与成像仪器ChemCam (Chemistry and Camera complex)用于分析和确定岩石矿物成分与组成。

3 火星表面含水矿物识别方法与成果

20世纪90年代以来开展的一系列火星探测任务已经在火星表面探测到大量的含水硅酸盐矿物和蒸发盐矿物等含水矿物(图2)，它们主要分布在火星南部高原诺亚纪古老地壳上(Ehlmann和Edwards，2014)。下面展开介绍火星表面含水硅酸盐矿物和蒸发盐矿物的识别方法与最新探测成果。

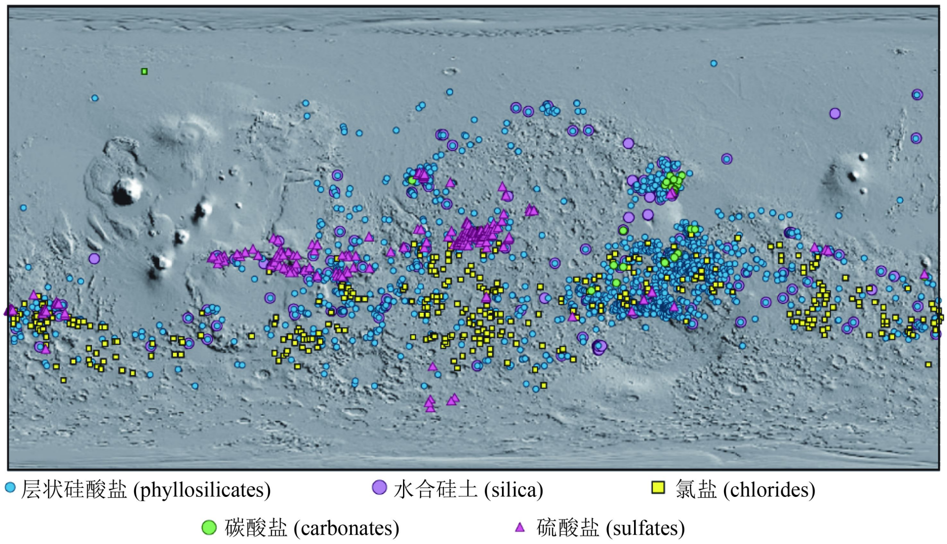

图 2 火星表面主要含水矿物全球分布

Fig. 2 Global distribution of the major classes of aqueous minerals on Martian surface

3.1 含水矿物探测识别方法

目前火星表面含水矿物探测最主要的数据源是OMEGA和CRISM高光谱数据，各种含水矿物在二者的光谱范围内基本都有其特定的诊断吸收光谱特征，因此，Poulet等人(2007)、Ody等人

(2012)和Loizeau等人(2007)针对OMEGA高光谱数据，Pelkey等人(2007)和Viviano-Beck等人(2014)针对CRISM高光谱数据分别设计了一系列表征光谱特征的光谱指数用来判断特定类型矿物存在与否，如光谱比值、光谱吸收深度等。表3给出了火星表面含水矿物探测常用光谱指数。

表 3　火星表面含水矿物探测常用光谱指数(Loizeau 等，2007、Poulet 等，2007、Pelkey 等，2007和Viviano-Beck 等，2014)

Table 3　Summary parameters commonly used for aqueous mineral detection on Mars, after Loizeau, et al., 2007, Poulet, et al., 2007, Pelkey, et al., 2007 and Viviano-Beck, et al., 2014

高光谱数据源	光谱指数名称	计算公式	感兴趣含水矿物
OMEGA	Hydrous minerals	$1-(R1930+R1940)/(R1830+R2120)$	含水矿物
	Al-smectites	$1-(R2190+R2200)/(R2150+R2270)$	层状铝硅酸盐
	Fe/Mg-smectites	$1-R2300/(0.25\times R2260+0.25\times R2270+0.5\times R2340)$	层状铁镁硅酸盐
CRISM	BD1400	$1-(R1395/(a\times R1330+b\times R1467))$	水化或羟基化矿物
	BD1900	$0.5\times(1-(R1930/(a\times R1850+b\times R2067)))+0.5\times(1-R1985/(a\times R1850+b\times R2067))$	含水矿物
	BD2100	$1-(R2132/(a\times R1930+b\times R2250))$	单水矿物
	BD2210	$1-(R2210/(a\times R2165+b\times R2250))$	层状铝硅酸盐
	BD2290	$1-(R2290/(a\times R2250+b\times R2350))$	层状铁镁硅酸盐
	D2300	$1-((CR2290+CR2320+CR2330)/(CR2140+CR2170+CR2210))$	层状硅酸盐矿物
	SINDEX	$1-((a\times R2120+b\times R2400)/R2290)$	含水硫酸盐矿物
	D2400	$1-((CR2390+CR2430)/(CR2290+CR2320))$	含水硫酸盐矿物
	BD2500	$1-(R2480/(a\times R2364+b\times R2570))$	碳酸镁矿物

注：Rn为相应波长处的反射率，n为波长，a和b代表了波长距离比例权重，CR为包络线去除后数值。

光谱指数适用于判断与研究大范围内特定类型矿物的存在性，但是由于许多矿物具有相同的吸收特征，如层状硅酸盐与单水硫酸盐这两种含水矿物在1.9 μm附近都具有吸收特征，因此单独使用光谱指数BD1900无法区分这两类矿物，还需要提取感兴趣区(如5×5窗口)的平均光谱，基于这两类矿物各自独特的诊断性光谱吸收特征，结合光谱匹配模型鉴定和判断具体矿物类别，如光谱特征拟合模型和光谱角填图模型等。此外，光谱指数只对特定波长位置处(通常为吸收峰位置)的光谱形状敏感，它们无法综合考虑光谱在整个波长范围内的谱形。因此，需要综合使用多个光谱指数或光谱特征进行矿物检测与判定以提高识别准确性，如利用专家系统(Clark 等，2003；Ehlmann 等，2016)。

3.2　含水硅酸盐矿物探测识别成果

火星表面探测到的含水硅酸盐矿物(hydrous silicates)绝大多数是具有层状结构的粘土矿物。粘土矿物是在一定的地质环境和气候条件下形成并广泛分布于地表，矿物结构中的水主要以中性水分子形式(吸附水或结晶水)或者羟基等形式(结构水)存在，其形成方式主要有3种：风化作用、热液作用和沉积成岩作用(徐叶净和左文喆，2013)。粘土矿物主要包括具层状结构的高岭石族矿物，蒙脱石族矿物，伊利石族矿物和蛭石族矿物，具过渡性层链状结构的坡缕石和海泡石族矿物，具混层结构的矿物以及非晶质的水铝英石等(表4)。此外，绿帘石、水合硅土和葡萄石，以及具有架状结构的沸石在火星表面也多有发现。在可见近红外波段范围内，含水硅酸盐矿物中由水引起的吸收特征一般位于1.4 μm和1.9 μm附近，且矿物中“含水量”越高，吸收深度越明显。粘土矿物中由羟基引起的吸收特征一般位于2.2 μm和2.3 μm附近，而沸石矿物中由羟基导致的吸收特征位于2.5 μm附近。这些吸收峰位置的细微差别反映了矿物结构中阳离子的差异(图3)。因此，含水硅酸盐矿物中的吸附水，结晶水或者结构水都可以利用其特定的光谱吸收特征进行识别(Bishop，2005)。

表 4 粘土矿物主要类别简表(方邺森(1985)和Mukherjee(2013))

Table 4 Category for major classes of clay minerals, after Fang(1985) and Mukherjee(2013)

晶体结构		结构单元层类型		层间物	族	典型矿物
晶质	层状结构	简单层状	1∶1型	有或无水分子	高岭石	高岭石、地开石、埃洛石等
			2∶1型	阳离子或水化阳离子	蒙脱石	蒙脱石、绿脱石、皂石等
					伊利石	伊利石、水云母、海绿石等
				氢氧化物	绿泥石	绿泥石
		混层状	有序混层	累托石、水黑云母、滑间皂石、绿泥间蛭石、绿泥间蒙石、绿泥间滑石、云间蒙石、绿泥间蜡石等伊利石-蒙脱石组合、绿泥石-蒙脱石组合等		
			无序混层	伊利石—蒙脱石—绿泥石组合等		
	层链状结构		2∶1型	水化阳离子	海泡石	坡缕石、海泡石
半晶质				伊毛缟石		
非晶质				水铝英石		

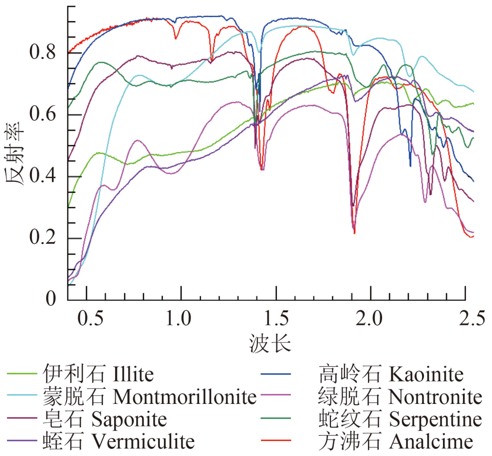

图 3 常见含水硅酸盐矿物反射光谱(光谱来自USGS地物反射光谱数据库(Clark 等，2007))

Fig. 3 Reflectance spectra of hydrous silicates(spectra are from USGS spectral library(Clark, et al., 2007))

OMEGA数据揭示了火星表面矿物的多样性和复杂性，它探测到绿脱石、绿泥石和蒙脱石等层状硅酸盐矿物(Bibring 等，2005)，石膏、水镁矾和多水硫酸盐等含水硫酸盐矿物(Bibring 等，2005；Gendrin 等，2005)，低钙辉石、高钙辉石和橄榄石等造岩矿物(Mustard 等，2005)。Poulet等人(2005)进一步研究了硫酸盐和层状硅酸盐这两类水合蚀变产物的分布特征及它们所反映的不同的火星早期气候环境。Loizeau等人(2007)在Mawrth Vallis分辨出层状铝硅酸盐矿物和层状铁镁硅酸盐矿物，如蒙脱石和绿脱石，发现它们均位于亮色露头上，并受到强烈侵蚀。CRISM在OEMGA探测的基础上进一步细化了火星表面矿物类型与组合模式。Ehlmann等人(2009)在Nili Fossae首次探测到出露的蛇纹石和方沸石，并识别出绿脱石、绿泥石、葡萄石、高岭石、伊利石、蛋白石、碳酸盐、多水硫酸盐等含水矿物。McKeown等人(2009)和Noe Dobrea等人(2010)在Mawrth Vallis识别出绿脱石、皂石、蛇纹石、绿泥石、黑云母以及蛭石等含水硅酸盐矿物，并在上覆于含铁镁硅酸盐矿物地质单元的地层中识别出蒙脱石、高岭石、水合硅土等层状铝硅酸盐矿物，同时还探讨了它们可能的形成过程和古气候指示意义。Loizeau等人(2012)对Tyrrhena Terra的含水硅酸盐矿物类别与分布进行了详细研究，发现它们主要为沸石、葡萄石、含镁绿泥石、富镁蒙脱石以及混层矿物等，且大部分矿物分布于撞击坑溅射席、坑壁及边缘和中央峰。

除轨道器光谱仪探测外，机遇号巡视器在Endeavour撞击坑边缘的Matijevic土丘首次实地探测到含有层状铁镁硅酸盐类粘土矿物的岩层露头(Arvidson 等, 2013)，粘土矿物的发现表明当时可能局部存在近于中性的水环境，这更有利于生命存在(Squyres，2012；Squyres和Arvidson，2013)。作为好奇号巡视器的着陆区，光谱仪观测显示Gale撞击坑堆积着大量层状特征明显的粘土矿物和硫酸盐矿物，好奇号巡视器就位分析验证了该观测结论。如在Yellowknife Bay采集的粉末状泥岩样品就位化学分析结果显示，样品中含有最高达20 wt.%的粘土矿物(Bristow 等，2015)，该区域一处约5 m厚的沉积物上还检测到可能为石膏的硫酸盐脉(Grotzinger 等，2014；Nachon 等，2014)。

3.3 蒸发盐矿物探测识别结果

蒸发盐矿物是经蒸发和浓缩，卤水中的盐类物质在干涸条件下依照不同的溶解度结晶而成的水溶性沉积矿物，包括硫酸盐、碳酸盐、氯盐、硝酸盐、硼酸盐等矿物。火星表面各类蒸发盐矿

物记录了其沉积时的古环境古气候信息，不同的蒸发盐矿物类别和含量反映了沉积时性质各异的水溶液环境，Bibring等人(2006)根据OMEGA高光谱数据在不同地质年龄地区探测的矿物的全球分布规律特征，将火星不同地质历史时代的溶液环境划分为3个地球化学期：中性偏弱碱性的易于形成层状硅酸盐矿物的phyllosian时期、酸性的易于形成硫酸盐的theiikian时期和无溶液环境易于形成铁氧化物的siderikian时期。因此蒸发盐矿物研究不仅对于探讨火星不同地质历史时期岩石圈、水圈和大气圈的相互作用关系具有重要意义，还对研究火星地质演化过程有重要指示意义。

3.3.1 硫酸盐矿物

硫酸盐矿物是火星表面常见的蒸发盐矿物，它们的矿物结构中往往含有以不同形式存在的水，如黄钾铁矾与明矾石晶体结构中含有羟基，硫酸钙晶体结构中含有分子水。含水硫酸盐矿物反射光谱的吸收峰位置取决于含水量多少(表5和图4)。

表 5 常见蒸发盐矿物光谱吸收峰(Ehlmann 等，2008和Lichtenberg 等，2010)

Table 5 Spectral absorptions of common evaporites, after Ehlmann, et al., 2008 and Lichtenberg, et al., 2010

蒸发盐矿物	主要吸收峰位置/μm
单水硫酸盐矿物	2.1, 2.4
多水硫酸盐矿物	1.4, 1.9, 2.4
碳酸盐矿物	2.3, 2.5

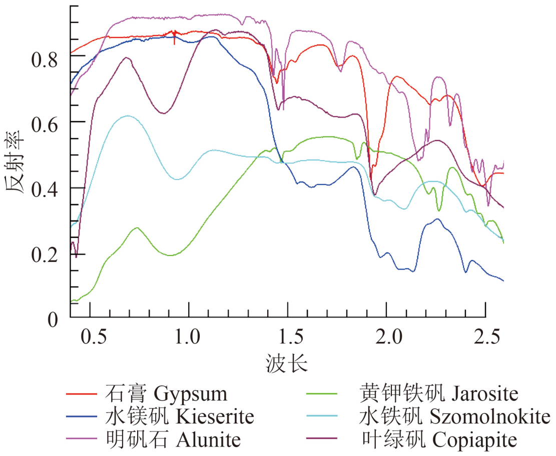

图 4 常见硫酸盐矿物反射光谱(光谱来自USGS地物反射光谱数据库(Clark 等，2007))

Fig. 4 Reflectance spectra of sulfates (spectra are from USGS spectral library (Clark等，2007))

研究人员通过分析OMEGA和CRISM光谱仪数据在火星表面识别出形成于各种水溶液环境的硫酸盐矿物。Langevin等人(2005a)利用OMEGA数据在火星环北极低反照率暗色区域发现大量可能为石膏的富钙硫酸盐矿物，面积约为60×200 km^2。Gendrin等人(2005)在Valles Marineris、Margaritifer Sinus和Terra Meridiani等亮色调层状沉积物发育地区发现许多水合含镁硫酸盐矿物，并根据OMEGA光谱吸收特征将其分为3类：第1类可能为水镁矾($MgSO_4 \cdot H_2O$)的单水硫酸盐矿物，第2类可能为生石膏($CaSO_4 \cdot 2H_2O$)或熟石膏($2CaSO_4 \cdot H_2O$)的硫酸钙矿物，以及第3类可能为泻盐($MgSO_4 \cdot 7H_2O$)，或叶绿矾($Fe^{2+}Fe^{3+}(SO_4)_6(OH)_2 \cdot 20H_2O$)，或铁明矾($Fe^{2+}Al_2(SO_4)_4 \cdot 22H_2O$)的多水硫酸盐矿物。Arvidson等人(2005)和Wendt等人(2011)分别在Meridiani平原和Ophir Chasma发现了水镁矾矿物的存在。Farrand等人(2009)根据CRISM光谱特征在Mawrth Vallis一块约3×5 km^{2}的卵形凹陷内识别出含钾的硫酸铁矿物黄钾铁矾($KFe_3(SO_4)_2(OH)_6$)，Wray等人(2010)还在该地区一条外流沟渠底部识别出硫酸钙矿物熟石膏。Lichtenberg等人(2010)通过与实验室合成矿物光谱比对分析，在Aram Chaos观察到分层不整合的羟基硫酸铁($Fe(OH)SO_4$)，单水硫酸亚铁矿物水铁矾($FeSO_4 \cdot H_2O$)和多水硫酸亚铁矿物水绿矾($FeSO_4 \cdot 7H_2O$)。此外，Swayze等人(2008)和Ehlmann等人(2016)在位于Terra Sirenum地区直径约65 km的Cross撞击坑内(30°S, 158°W)还探测到明矾石矿物($KAl_3(SO_4)_2(OH)_6$)，有些还与高岭石混合，首次证实了火星过去曾存在富铝酸性盐水。

火星车就位化学分析结果同样显示火星表面存在多种硫酸盐矿物。机遇号巡视器搭载的穆斯堡尔谱仪在位于Meridiani Planum的Eagle撞击坑探测到富含黄钾铁矾和赤铁矿的露头(Klingelhöfer 等，2004)。勇气号在巡视Gusev撞击坑的过程中，穆斯堡尔谱仪在浅表层约10 cm厚的土壤内发现了大量硫酸镁、少量硫酸钙以及疑似硫酸铁矿物(Wang 等，2006)。如前文所述，好奇号巡视器搭载的X射线谱仪在Yellowknife Bay的泥岩中探测到熟石膏和无水硫酸盐矿物(Vaniman 等，2014)。

3.3.2 碳酸盐矿物

碳酸盐矿物是镁、铁、钙等元素的金属阳离子与碳酸根相结合形成的岛状、链状和层状3种结构类型的化合物，主要由沉积作用形成。在可见近红外光谱范围内，碳酸盐矿物的具体类别主要

通过光谱在2.3 μm和2.5 μm附近同时存在的吸收峰位置的细微差别来区分(表5和图5)。同时，光谱在3.4 μm和3.9 μm附近存在的微弱吸收特征也可以帮助确认碳酸盐存在与否(Ehlmann 等，2008；Ehlmann 等，2009；Viviano-Beck 等，2014)。

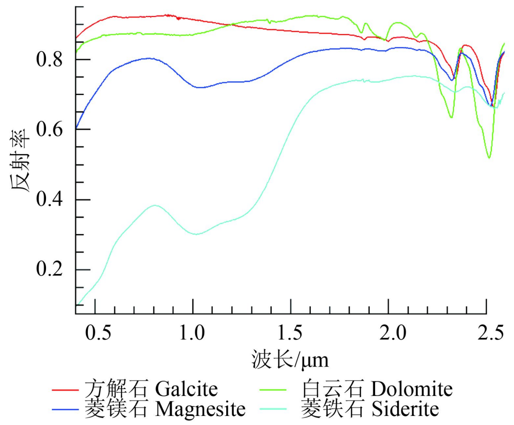

图 5 常见碳酸盐矿物反射光谱(光谱来自USGS地物反射光谱数据库(Clark等，2007))

Fig. 5 Reflectance spectra of carbonates (spectra are from USGS spectral library (Clark, et al., 2007))

火星表面目前探测到的碳酸盐矿物主要集中在Isdis盆地以西的Nili Fossae和Hellas盆地以北的Tyrrhena Terra(图2)。Ehlmann等人(2008)利用CRISM高光谱数据首先在火星表面Nili Fossae发现了菱镁石矿物($MgCO_3$)，Brown等人(2010b)进一步研究了Nili Fossae的碳酸盐和粘土矿物蚀变组合及其地质和生物学意义。此后，火星表面出露的碳酸盐矿物不断被发现(Michalski和Niles，2010；Morris 等，2010；Wray 等，2011；Carter和Poulet，2012)。Michalski和Niles(2010)在Syrtis Major火山附近Leighton撞击坑中央峰探测到钙铁碳酸盐矿物出露，并推断火星表面曾经大量存在的碳酸盐被后期火山活动喷发物所掩埋。Wray等人(2011)在Huygens撞击坑内部观测到的CRISM光谱特征与菱铁石($FeCO_3$)、方解石($CaCO_3$)等碳酸盐矿物的光谱特征吻合较好。

勇气号巡视器在Gusev撞击坑Columbia山的Comanche露头区探测到高达16—34 wt.% 的镁铁碳酸盐矿物(Morris 等，2010)，Carter和Poulet(2012)利用CRISM数据在该露头更大范围内发现了碳酸镁矿物。此外，凤凰号着陆器在着陆点的土壤中发现含3—5 wt.%的碳酸钙矿物(Boynton 等，2009)。

3.3.3 氯盐及高氯酸盐矿物

氯盐矿物光谱在红外波段具有较高的表观发射率，且表现出蓝坡现象。与火星表面探测到的其他矿物光谱相比，氯盐矿物光谱在可见近红外谱段除具有红坡现象外，再无其他明显吸收特征(Glotch 等，2010；Viviano-Beck 等，2014；Glotch 等，2016)，研究人员可以综合利用THEMIS和CRISM独特的光谱特征识别和确认氯盐的存在，并分析它们的地质环境指示意义(Murchie 等，2009；Wray 等，2009)。Osterloo等人(2008)通过分析THEMIS和TES热红外数据，首次在火星南部高原低反照率区域发现了约200处具有特殊光谱特征的沉积物，并认为它们含有氯盐。进一步研究显示这些含氯盐沉积物具有以下特征(Osterloo 等，2010)：(1)广泛分布于南部高原诺亚纪和西方纪地质单元内，约有640处；(2)局部热惯量较高，表明沉积物部分固结；(3)发育于各类地貌之上，且通常还发育有裂隙；(4)大部分沉积物位于局部地势低洼区域。Ruesch等人(2012)利用OMEGA数据系统分析了这些含氯盐沉积物的物质成分，研究表明这些含氯盐沉积物成因可能与地下水上涌或地表径流蒸发有关。

根据海盗号着陆器搭载的X射线荧光谱仪在着陆点土壤中探测到的硫、氯等元素，Clark等人(1976)以及Clark和Van Hart(1981)推断火星表面存在硫酸盐、氯盐等盐类矿物。索杰娜巡视器搭载的α粒子X射线谱仪也在着陆点探测到了氯元素(Rieder 等，1997)。除氯盐外，凤凰号着陆器对火星北极土壤的检测分析显示土壤中含有高氯酸盐矿物(Cull 等，2010)。在研究火星表面Palikir撞击坑(41.6°S, 157.7°W)、Horowitz撞击坑(32.1°S, 140.7°E)、Hale撞击坑(35.7°S, 36.6°W)和Coprates深谷(13.4°S, 61.4°W)季节性斜坡条纹成因机制的过程中，Ojha等人(2013, 2014, 2015)证实目前火星表面仍存在液态卤水，并通过光谱分析确定其主要成分为高氯酸镁，高氯酸钠和氯酸镁。

火星表面探测到的多样性含水矿物表明，随着火星探测任务中高光谱仪光谱分辨率和空间分辨率的逐步提高，火星表面可识别的含水矿物不断增多(表6)。由于不同的含水矿物形成的溶液环境各不相同，因此这些含水矿物的探测和分布特征研究为分析火星表面各类含水矿物形成的古地理环境和背景提供了重要的基础数据。如火星诺亚纪地壳上遍布的河谷网络、沟渠等流水侵蚀地貌

以及撞击热液系统生成的蚀变次生矿物表明了火星早期可能温暖而湿润(Baker，2006；McSween，2006；Schwenzer 等，2012)。广泛分布于南半球地质单元内的氯盐矿物则表明了这些地区曾经有过大量卤水(如古盐湖)，火星地质历史中后期的持续干旱作用导致这些氯盐的析出(Golombek 等，2005；El-Maarry 等，2013)。赵健楠和肖龙(2016)在全面总结火星古湖泊研究现状时指出，大部分古湖泊最后一次经历火山和冰川作用等改造事件的时间为西方纪至早亚马逊纪(约3.7—1.4 Ga)。在已识别出的存在湖泊沉积物的100 多个古湖泊中，只有近20个探测到含水矿物，导致这种情况的可能原因有3种：(1)光谱数据覆盖范围有限；(2)含水矿物被后期改造物质(如风成灰尘)覆盖；(3)火星古湖泊内沉积物与地球不同。由于这些含水矿物均为运移而来，而非原位生成，可能指示了这些湖泊持续存在时间短暂，不足以形成含水矿物。“机遇号”、“勇气号”和“好奇号”等巡视器均在各自就位探测的古湖泊区域探测到含水矿物，与轨道器光谱仪遥感探测的结果相一致，指示了火星表面曾经存在水的活动，表面物质经历了广泛的蚀变作用。研究人员通过不断研究火星表面含水矿物的类型、分布特征与地质环境，确定火星上曾经长期存在不同化学性质的液态水，它们在火星诺亚纪和西方纪时期较为活跃，且确有适宜生命起源和延续的自然地理环境出现过，但目前还没有发现任何生命遗迹或迹象(Bibring 等，2006；Bishop 等，2013；Carter 等，2013)。与此同时，研究人员也逐步利用高光谱数据针对火星表面含水矿物开展了定量反演。

表 6　火星表面目前探测到的主要含水矿物(Ehlmann和Edwards(2014)、Viviano-Beck 等(2014)和Viviano-Beck 等(2015))

Table 6　Major aqueous minerals detected on Mars from present orbital and in-situ datasets, after Ehlmann & Edwards, 2014, Viviano-Beck, et al., 2014 and Viviano-Beck, et al., 2015

含水矿物	矿物类别	中文名称	英文名称	通用化学式
含水硅酸盐矿物	层状硅酸盐矿物(粘土矿物为主)	高岭石	kaolinite	$Al_2Si_2O_5(OH)_4$
		蒙脱石	montmorillonite	$(Na, Ca)_{0.33}(Al, Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$
		伊利石	illite	$(K, H_3O)(Al, Mg, Fe)_2Al_xSi_{4-x}O_{10}(OH)_2$
		白云母	muscovite	$KAl_2[Si_3AlO_{10}](OH, F)_2$
		皂石	saponite	$Ca_{0.25}(Mg, Fe)_3((Si, Al)_4O_{10})(OH)_2 \cdot nH_2O$
		绿脱石	nontronite	$(Ca_{0.5}, Na)_{0.3}Fe_2(Si, Al)_4O_{10}(OH)_2 \cdot nH_2O$
		滑石	talc	$Mg_3Si_4O_{10}(OH)_2$
		蛇纹石	serpentine	$Mg_3Si_2O_5(OH)_4$
		蛭石	vermiculite	$(Mg, Fe^{2+}, Fe^{3+})_3[(Al, Si)_4O_{10}](OH)_2 \cdot 4H_2O$
		绿泥石	chlorite	$(Mg, Fe^{2+})_5Al(Si_3Al)O_{10}(OH)_8$
	其他含水矿物	方沸石	analcime	$NaAlSi_2O_6 \cdot H_2O$.
		绿帘石	epidote	$Ca_2Al_2(Fe^{3+}, Al)SiO_4][Si_2O_7]O(OH)$
		水合硅土	hydrated silica	$SiO_2 \cdot nH_2O$
		葡萄石	prehnite	$Ca_2Al(AlSi_3O_{10})(OH)_2$
蒸发盐矿物	硫酸盐矿物	单水硫酸盐(水镁矾和水铁矾等)	monohydrated sulfate	$FeSO_4 \cdot H_2O$和$MgSO_4 \cdot H_2O$等
		明矾石	alunite	$KAl_3(SO_4)_2(OH)_6$
		羟基硫酸铁	hydroxylated ferric sulfate	$Fe(OH)SO_4$
		黄钾铁矾	jarosite	$KFe_3(SO_4)_2(OH)_6$
		多水硫酸盐(水绿矾和泻盐等)	polyhydrated sulfate	$FeSO_4 \cdot 7H_2O$、$MgSO_4 \cdot 7H_2O$、$Fe^{2+}Fe^{3+}(SO_4)_6(OH)_2 \cdot 20H_2O$和$Fe^{2+}Al_2(SO_4)_4 \cdot 22H_2O$等
		石膏	gypsum	$CaSO_4 \cdot 2H_2O$
		熟石膏	bassanite	$CaSO_4 \cdot 0.5H_2O$
	碳酸盐矿物	方解石	Calcite	$CaCO_3$
		菱镁石	magnesite	$MgCO_3$
		菱铁石	siderite	$FeCO_3$
	氯盐及高氯酸盐	氯盐	chloride	$NaCl$和$MgCl_2$等
		高氯酸盐	perchlorate	$Ca(ClO_4)_2$和$Mg(ClO_4)_2$等

4 火星表面含水矿物定量反演方法与成果

火星表面岩石或土壤大多由多种矿物混合组成，因此无论是搭载于轨道器的光谱仪遥感测量的光谱，还是装载于火星车的光谱仪就位测量的光谱基本都是混合光谱。火星表面含水矿物定量反演主要是根据光谱的吸收峰位置和深度等特征，采用定性或定量的方法反演矿物的相对含量或丰度。

4.1 火星表面含水矿物定量反演方法

目前，火星表面含水矿物定量反演主要有吸收深度转换法和混合光谱分解法这两类方法。吸收深度转换法主要根据矿物光谱吸收峰深度与矿物含量基本呈线性相关的特点，利用光谱吸收峰深度的变化近似估算矿物的相对含量。由于光谱吸收峰深度受到光谱测量环境、光谱定标精度、光谱混合效应等多种因素的共同影响和干扰，该方法仍然具有不确定性。混合光谱分解法通过光谱解混模型定量反演矿物的丰度，它是目前火星表面含水矿物丰度反演最常用的方法。光谱解混模型主要有线性解混模型和非线性解混模型两大类。线性解混模型假定光谱仪获取的光谱是地表各组成矿物(端元)光谱的线性组合，各组成矿物光谱在混合光谱中的比例就是该矿物的丰度。它具有物理含义明确和模型简单易用的优点，适用于本质上属于或者基本属于线性混合的地物及在大尺度上可认为是线性混合的地物(如聚合型和整合型混合地物)。非线性解混模型通常根据产生混合光谱的物理机制或者直接应用数学分析方法构建光谱分解模型，它适用于小尺度的内部致密混合地物的光谱分析。火星表面矿物混合多属于致密混合，在可见近红外反射光谱范围内，非线性解混模型能够较好的反演矿物丰度和分析矿物成分，因而在火星表面矿物反演中得到了广泛应用。火星表面含水矿物反演常用的非线性解混模型包括Hapke模型(Hapke，2012；Edwards和Ehlmann，2015；Liu 等，2016)和Shkuratov模型(Shkuratov 等，1999；Poulet 等，2008, 2009a, 2009b, 2014)。

4.2 火星表面含水矿物定量反演成果

全球尺度上，Carter等人(2013)根据含水矿物的吸收特征峰位置，综合利用OMEGA和CRISM高光谱数据，采用光谱指数法等系统研究了火星表面含水矿物类型与全球分布特征，结果显示：(1)火星全球广泛分布有含水矿物，但含水硅酸盐矿物主要集中于南部古老高地；(2)火星北部低地发现的含水矿物赋存于具有不同地质年龄的地质单元内，且其成分表现出多样性特征；(3)大多数地球上存在的含水矿物族在火星上也同样能够探测到，如蒙脱石族、云母族、高岭土族、蛇纹石族、碳酸盐族等，火星上最常见的含水矿物是富含铁/镁/铝的层状硅酸盐矿物；(4)火星上的大多数含水矿物形成于诺亚纪中期之前，之后的西方纪和早诺亚纪仅发生了极少有限蚀变；(5)尽管赋存含水矿物的不同地质背景已经严重退化，但它们表明了含水矿物形成环境的多样性。常见于撞击坑中央峰和溅射物之上的含水矿物表明大规模的撞击挖掘作用使得掩埋的含水矿物出露，说明它们也许形成于火星浅地层或一定深度范围内。

局部尺度上，Combe等人(2008)在运用多端元线性光谱分解模型时，引入了代表无吸收特征矿物的光谱参与矿物丰度反演以减轻矿物颗粒大小和气溶胶散射对光谱的影响，模型反演的火星表面Syrtis Major、Aram沌地以及北极Olympia沙丘这3个区域的矿物丰度信息与前人工作吻合，表明该方法在不同的矿物环境下能够提供矿物丰度的初级近似结果，Le Mouélic等人(2009)将其应用于大规模的OMEGA数据分析，反演了火星表面橄榄石、单斜辉石和斜方辉石等矿物的分布与丰度。Poulet等人(2008)应用Shkuratov模型拟合火星Mawrth Vallis和Nili Fossae地区的OMEGA高光谱数据，分析层状硅酸盐露头的矿物丰度，反演结果显示Mawrth Vallis层状硅酸盐矿物远远较Nili Fossae丰富，表明该地区沉积岩或蚀变火成岩较为发育。Poulet等人(2014)还进一步反演了好奇号火星车曾经选定的4个候选着陆区的含水矿物丰度，结果显示Mawrth Vallis含水矿物丰度最高，达到了70%左右，Eberswalde撞击坑最低，为25%左右，这4个地区的矿物组合反映了不同的蚀变程度或含水矿物后期与无水矿物的混合程度。Farrand等人(2011)应用Shkuratov模型对火星Mawrth Vallis地区的CRISM高光谱数据进行非线性分解，解混结果显示该地区含层状铝硅酸盐矿物露头较含层状铁镁硅酸盐矿物露头蚀变程度高。Scudder等人(2015)利用Hapke模型将CRISM光谱反射率转换为

单次散射反照率后，定量反演了Cross撞击坑南缘辉石、橄榄石、斜长石和层状硅酸盐等矿物的丰度，结果显示层状硅酸盐矿物的丰度在特定区域最高可达20%。Liu等人(2016)将Melas深谷获取的CRISM光谱转换为单次散射反照率后，采用非负最小二乘线性算法解混。这对研究区过去存在的溶液环境和含水矿物的形成过程具有指示意义，如光谱解混结果显示混层的硫酸盐矿物和层状硅酸盐矿物具有不同的丰度(分别为~20%和~40%)，它们可能是玄武岩风化和蒸发共同作用形成的。帅通(2014)和Lin等人(2016)基于非线性与稀疏解混模型反演了Gale撞击坑好奇号巡视器登陆点附近区域含水矿物的丰度，反演结果与光谱指数法提取的含水矿物整体分布趋势基本一致，为火星表面含水矿物定量反演提供了一种新的思路。

这些矿物反演工作为精细研究火星表面含水矿物形成和演变历史提供了定量资料，但总体上反演工作还存在很大的局限性，目前仍是火星表面含水矿物遥感探测与反演的一大重点与难点。这一方面是由于火星大气与地球迥然不同，相应的大气校正算法还无法得到充分验证；另一方面是由于火星表面遍布撞击坑、冲沟、沙丘等，表面地貌特征差异大，光谱仪成像环境极为复杂，火星车就位探测区域极为有限，地球环境中适用的算法反演获取的火星表面含水矿物丰度的精度还无法得到确切验证。

5 结 语

火星表面含水矿物的探测证实了火星表面过去曾经存在水，不同地貌和地质环境下形成的含水矿物的类别随着时间推移逐步改变的现象揭示了火星表面水溶液环境化学性质丰富的演变历史。本文总结了20世纪90年代以来火星表面含水矿物探测主要使用的轨道器光谱仪数据源(热辐射光谱仪、热辐射成像系统、可见光及红外矿物填图光谱仪和紧凑型火星侦察成像光谱仪)和就位探测巡视器和着陆器数据源(火星探路者着陆器和索杰娜巡视器、勇气号巡视器、机遇号巡视器、凤凰号着陆器和好奇号巡视器)，详细介绍了火星表面已经探测到的各类含水硅酸盐矿物、硫酸盐矿物、碳酸盐矿物、氯盐及高氯酸盐矿物等含水矿物的光谱特征、矿物具体类别及分布特征，同时，本文还概括了火星表面含水矿物定量反演的主要方法与成果。这些研究成果对了解火星不同历史时期的水环境、火星表面地貌与地质演化过程、火星表面是否曾经具备支持生命存在的地质窗口等提供了重要依据。

目前，由于轨道器光谱仪分辨率的限制和定量反演算法的适用性，以及火星表面可能有地球上不存在的含水矿物，火星表面可能还存在尚未探测到的含水矿物。因此今后需要在实验室条件下精确测定地球上已知的各类含水矿物的光谱特征曲线，同时研制性能优秀的新型光谱仪提高光谱分辨率以增大火星表面可识别含水矿物识别的种类。在火星车能够提供火星表面真实验证数据的情况下，还需要针对火星大气特征和地貌特征，设计并交叉验证火星大气校正算法与表面含水矿物定量反演算法，在保证反演算法准确性与精度的前提下提高算法的健壮性与扩展性。

中国将于2020年发射火星探测轨道器和火星车，从比较行星学角度在地球上选择恰当区域，如青海大浪滩干盐湖开展含水矿物类比研究(Kong等，2014)，不仅有助于理解火星含水矿物的形成环境和过程，还可为中国火星探测任务着陆区评估选择及实施探测任务提供借鉴参考意义，因此，地球和火星含水矿物对比研究将是今后几年内的一个重要研究方向。

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Advances in aqueous minerals detection on Martian surface

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Abstract: Aqueous minerals are either minerals that form in water or formations that are related to water. The type of aqueous mineral depends on temperature, salinity, PH, and composition of the parent rock at their forming time, which provides important clues to understanding the past aqueous environments of Mars, delineating advantageous regions for life activities, and even searching for possible existing Martian life. Therefore, studies on aqueous mineral identification and spatial distribution pattern are of considerable scientific significances. This paper provides a comprehensive overview of the advances of aqueous minerals detection on Martian surface since the 1990s.

First, the major specifications of two data sources for mineral detection are introduced, including orbital spectrometers (TES, THEMIS, OMEGA, and CRISM) and in-situ landers/rovers (MPF/Sojourner, Spirit, Opportunity, Phoenix, and Curiosity). The spectrometers utilize either emission features in thermal infrared (TIR) or reflectance absorption characteristics in visible/near-infrared (VNIR) to identify and discriminate mineral types. Landers and rovers equipped with scientific instruments carry out the in-situ measurement to provide detailed component identification, abundance detection, and other analyses on the Martian surface soil, minerals, and rocks.

Second, the spectral features, specific types, and distribution patterns of aqueous minerals detected on Martian surface are illustrated in detail as bound water, adsorbed water, and structural OH in aqueous minerals can be remotely detected via their unique spectral characteristics. Although aqueous minerals are widespread on Mars, they are concentrated in the Noachian southern highlands. At present, the aqueous minerals detected and verified on Martian surface from orbital spectrometers and landers/rovers can be classified as hydrous silicate minerals, sulfates, carbonates, chlorides, and perchlorates.

Third, the major aqueous mineral quantitative retrieval methods, including absorption band depth conversion and spectral unmixing algorithms, are introduced. Compared with the linear unmixing model, the nonlinear spectral unmixing model can characterize mineral composition and retrieval mineral abundance with higher precision; therefore, it has been extensively used for the quantitative retrieval of aqueous mineral on Martian surface. The most commonly used nonlinear spectral unmixing models are the Hapke and Shkuratov models. The retrieval works provide fine quantitative data for inferring the formation and evolution history of aqueous mineral on Martian surface. However, numerous limitations exist, which are still important and difficult issues in aqueous mineral detection and retrieval via remote sensing. Furthermore, the retrieval advances at global and local scales, as well as their geological implications for Mars, are summarized.

The detection of aqueous minerals confirms the existence of past water solution environment on Martian surface, and the phenomenon of diverse aqueous mineral categories that formed in various geomorphologies and geological contexts gradually changes over time reveals the evolution diversity of the chemical properties of water solution. Considering these two conditions, the paper finally proposes an analog study between Earth and Mars that should be carried out from the viewpoint of comparative planetology on the formation environment and process of aqueous minerals, which has important reference significance for the Mars exploration mission of China that is planned to be launched in 2020.

Key words: Martian surface, aqueous mineral, remote sensing detection, in-situ detection, quantitative retrieval, comparative planetology

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