Mark Denny & Alan McFadzean

Rocket Science

From Fireworks — to the — Photon Drive

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Preface—Lift off

Many readers are interested in rockets but not in mathematics, and so your authors have to square a circle—to present a technical subject in a manner that is insightful without presenting it using the language that provides the insight. We do this by choosing carefully which aspects of rocketry to analyze mathematically and by relegating *all* the math to a technical Appendix. Thus, those of you who do not care to read math analysis can stick to the main text, where smooth and continuous prose will elucidate the rocketry (you will have to take our word for it that the analysis is right). Those readers who crave math—and they are not such rare creatures as you might suppose—will find that the derivations provided in the technical appendix are complete, though condensed. High school physics will get you through the main text; undergraduate physics and math are needed for the Appendix.

We generally use scientific units and notation. Thus: meters instead of feet, and kilometers instead of miles, though we will provide both occasionally, especially in a historical context. Speed is here measured in meters per second and denoted ms^{-1} rather than m/s. Here is your first conversion: $1\ ms^{-1} = 2.24$ mph. Acceleration is measured in ms^{-2}: the acceleration due to gravity at the Earth's surface is $g = 9.8\ ms^{-2}$ = 32 feet per second per second. In dimensionless units we say this is 1 g (so that an acceleration of $25\ ms^{-2}$ is $2.55g$). We use G to represent the force that results from acceleration g, so that an astronaut in a centrifuge subjected to $2g$ acceleration will feel a G-force of two—double his weight.

There are two authors. We wrote different chapters and when we combined them to form an early version of the full manuscript we found that, naturally enough, some of the more important subject matter was repeated—with stylistic differences. Generally we have expunged one or other account of such repeated material (leaving the clearer version) but occasionally we have retained both, where it seems to aid clarity or emphasize a significant point.

A note on terminology: The first human in space was Yuri Gagarin, a Soviet citizen. The Soviets and their Russian successors have always called their space travelers ‘cosmonauts’; everyone else’s are known as ‘astronauts’. The ‘cosmo’ comes from cosmos, meaning the whole Universe, and the ‘astro’ comes from stars. For simplicity we will call them all astronauts and, so far, none of them have been further than the Moon. Still, it’s early days… In the same vein we sometimes use ‘Russian’ for ‘Soviet’ because the USSR can be considered as the Russian Empire under new management. Following the collapse of the USSR, we stick with Russian.

More terminology: like all technical subjects, rocketry and space travel are full of jargon, acronyms and abbreviations. Here are a few of the more common ones to get you in the mood—we will define them in the text when first introduced, but in case you later forget what they stand for, you can refer back to this preface.

- ABM *Anti-Ballistic Missile*
- AI *Artificial Intelligence*
- CONOPS *CONcept of OPerationS*
- ESA *European Space Agency*
- GNC *Guidance, Navigation and Control*
- GSO *GeoSynchronous Orbit or GeoStationary Orbit*
- GTO *Geostationary Transfer Orbit*
- ICBM *Inter-Continental Ballistic Missile*
- IRBM *Intermediate Range Ballistic Missile*
- ISS *International Space Station*
- LEO *Low Earth Orbit*
- MIRV *Multiple Independently-Targetable Re-Entry Vehicle*
- NASA *National Aeronautics and Space Administration*
- NEO *Near-Earth Orbit*
- R&D *Research and Development*
- RPG *Rocket-Propelled Grenade*
- SSTO *Single Stage To Orbit*

At the time of writing we are marking the 50th anniversary of the first *Apollo* Moon landing. The rocket that lifted the lunar module with its human payload out of the grip of Earth’s gravity was the *Saturn V*—the most powerful rocket flown to date. We will see in this book that rockets as we know them peaked with *Saturn V*—future rockets will be different beasts, with more brains (the computing power aboard *Saturn V* was feeble compared with what you carry around in your smartphone) and less brawn. They will perform a wider range of tasks, for which they will be fine-tuned—some of these future rockets won’t even *be* rockets. A hundred years from now we will lift ourselves into orbit in an entirely different manner that circumvents the need for chemical rocket motors—which are *only just* capable of overcoming Earth's gravity, as we will see. Once in orbit, we will send people to Mars or the stars with machines that are quite different again. This book celebrates the old-fashioned beasts like *Saturn V*, looking back and a little forward (these dinosaurs will be with us for a few more decades), but also casts a curiosity-filled glance at their replacements.

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Contents

1

Why Rockets?

Why indeed. Rockets were first employed over a thousand years ago as fireworks and as weapons of war, and latterly—for the past sixty years—as vehicles for getting payloads into space. As weapons of war, they were something of an adornment for most of their existence—they looked impressive but served little function, playing second fiddle to arrows and then artillery shells. Only in the last century have they emerged from the shadows as engines of megadeath (which did tend to grab people's attention). But so what?

Neither fireworks nor ICBMs (Inter-Continental Ballistic Missiles) are why we find rockets so intriguing. The primary reason why rockets have routinely grabbed the headlines and technological limelight in recent generations is because they are the only means we currently have of sending payloads into space—therein lies their fascination.

This preliminary section of the book is a guide—an outline—to many of the subjects within the multifaceted subject of rocketry, telling where in later chapters you will find them discussed, analyzed, dissected or otherwise taken apart.

You must find rockets interesting, or you wouldn't have picked up this book. We must find them interesting to have written it. In fact, when we submitted our book proposal to the publisher, we noted that they already had several rocket-related books in their catalog of titles—so lots of other people must find something interesting about these odd, extreme machines.

Oddity #1: a rocket is a machine for moving rocket propellant. The truth and significance of this bizarre tautology will become clear in Chap. 3, where we address and explain the key physics underlying rocketry. Oddity #2: the first rocket propellant was invented before the first rocket (explained in Chap. 2,

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where we delve into rocket history). Oddity #3: the theory of rocketry was developed a few years before the theory of flight—in the same year that the Wright brothers made the first brief and tentative foray into powered flight on a freezing day in December 1903. Flight happened first only because of the difficulties of getting *to* space.

Part of the appeal of rockets is surely their strangeness and variety (emphasized in Fig. 1.1, which shows two very different rocket launchers). The contrast in scale is perhaps significant in pinning down the appeal. We are familiar with firework rockets that are launched from bottles, and so arguably can better appreciate the massive machines we watch on TV launching satellites into space. There is a continuum of scale between stick rockets launched from milk bottles and the *Saturn V* launching Moon probes: rocket enthusiasts—members of rocket societies that have been around for nearly a century in many countries across the world (Chap. 2)—design, build and launch rockets today that might rise only twenty meters into the air or might reach the edge of space, as we will see. The engineering of big, heavy-lift rockets such as *Saturn V* is very different from the engineering of little firework rockets but the propulsion physics is the same (Chaps. 3 and 4).

Fig. 1.1 Two rocket launch pads. (a) Launch Pad 39-A, at the Kennedy Space Center in Florida. *Apollo-11* was launched from here atop the famous *Saturn V* heavy-lift rocket, as were the first and last *Space Shuttles*. (NASA has leased 39A to SpaceX for 20 years.) 39A is constructed from 120,000 cubic yards (92,000 m^3) of concrete and 8,000 tons of reinforced steel, and took two years to build. *NASA image*. (b) Glass milk bottle, used to launch 2-oz stick rocket fireworks. (Can also be used to hold milk.) Constructed from 0.0005 tons of glass. *MBS Wholesale Supplies image*.

The main reason why people like rockets, we repeat, is the connection between rockets and space. Space—the black nothingness above our atmosphere, the cold vacuum between the stars—has been a source of fascination ever since people began to look up at night. All the Earth's land has now been explored, and even the depths of the world's oceans have been measured, mapped and categorized (if only by remote-controlled submarines); what is left to explore is out there in space. How to get up into space—to investigate it, to help us understand how the universe ticks, to colonize other worlds—is a practical question that has occupied the imaginations of some far-seeing engineers, scientists and writers since the end of the nineteenth century (Chap. 2). Rocketry is the only technology that can possibly get us from the Earth's surface into space. (That observation, true for the last hundred years, may be about to change (Chap. 7)). Not just get us there: rockets are (almost) the *only* means of propulsion in space (why won't jets work? See Chap. 3).

The Space Race, the public face of the Cold War, was to some degree a competition between two groups of ex-Nazi rocket scientists (Chap. 2), at least in its early stages. The difficulties of getting human payloads to the Moon were partly physics, but mostly engineering (Chaps. 4 and 5). How do you control a hundred-meter-high stack of toxic, corrosive and explosive propellant on the launch pad? What prevented a *Saturn V* from keeling over in the first few seconds after lift-off, when the rocket was inching its way off the launch pad? Answers in Chaps. 5 and 6, where we get to tell you about guidance and control systems. Chemistry also played a role, in deriving the best possible propellants (Chap. 5). All these rocket developments arose over decades of accumulated expertise, punctuated by plenty of unsuccessful launches, explosions on the launch pad and in the sky, plus failed components during launch and in space. The pure physics of rocketry in the Earth's atmosphere and in the vacuum of space had been worked out well before the first successful mass-produced rocket (the German V2) ever got off the launch pad (in contrast to flight through the air, where theory initially trailed practice). The difficulties and practical problems that needed to be solved so that humankind could progress from a World War Two (WW2) ballistic missile rocket to a Moonshot rocket took a generation to overcome and had little to do with physics; as we will see, they were almost all problems of engineering.

The rockets that are associated with the launch pad of Fig. 1.1a are the main subject of this book; those associated with the launch pad of Fig. 1.1b are discussed here. Skyrockets are the traditional aerial firework. For large public displays nowadays, aerial fireworks are often launched via a mortar, but in the past and in many backyards today, a small skyrocket firework is attached to a stick placed in a milk bottle for launching. The stick is a simple example of *fin stabilization*. The idea is that the rocket accelerates out of the milk bottle very quickly so that by the time it loses contact with the bottle, it is traveling fast enough for the stick to be sufficiently influenced by aerodynamic drag to keep the rocket vertical (Chap. 5). Thus the milk bottle orients the rocket vertically while the rocket is being launched, and the stick keeps it oriented vertically during flight. That is the theory, anyway, and it works most of the time.

Technically classed as *low explosive pyrotechnic devices*, fireworks began simply as gunpowder packed into bamboo tubes. Invented in China in the early ninth century, almost certainly as a consequence of the earlier invention of gunpowder (of which, much more later), fireworks displays became a big deal in China, and have remained pretty much a big deal there ever since. China produces more fireworks than any other country; this was the case a thousand years ago and it is true today. Professional fireworks makers and fireworks display organizers existed in China from very early days. Fireworks were considered propitious: they helped to ward off evil spirits, celebrate major festivals and mark state occasions. Today the same applies, with greater emphasis on key festivals and not so much on evil spirits. Many of the world's nations stage fireworks displays for big occasions, such as the Moon Festival in China and the Fourth of July in the United States (fireworks have celebrated US Independence Day since the very first one). Especially, New Year's Day is brought in by many of the world's nations at midnight local time with enormous displays of aerial pyrotechnics that are broadcast around the globe.

Modern fireworks are, unsurprisingly, much more hi-tech than the first gunpowder-packed bamboo devices. The current largest aerial firework weighs half a ton, and is fired from a mortar in Japan every 9th/10th September to an altitude of 850 m (half a mile) where it explodes into a rosette 800 m in diameter. The world's tallest building (at 828 m) is the Burj Khalifa in Dubai; every New Year it is the platform for an enormous pyrotechnic display as 1.6 tons of fireworks erupt from all four sides (and from the top) over a 10-minute period. The current record for the fastest rate of letting off fireworks was also set in Dubai, in 2013: 479,651 shells were fired into the air in six minutes. That's 1,332 shells per second. The largest ever firework display was another New Year celebration, this time in 2015–16 in the Philippines: 810,904 were let off over a 1 ½ hour period, in pouring rain. Many of these pyrotechnic displays—and others not described here such as the world's largest Catherine Wheel firework and the world's largest sparkler—can be viewed on Youtube.[1]

[1] For firework displays captured on Youtube, see e.g. *What if You Burn 10 000 Sparklers?*, *Largest Catherine Wheel On Earth Guinness World Record*, *Watch Dubai New Year 2019 fireworks in full*. For more details about all aspects of fireworks, see Plimpton (1984), Werrett (2010). See also the online Wired article by J. Greenberg: *What's Inside Fireworks: Glitter Starch and Gunpowder* at www.wired.com/2015/07/whats-inside-fireworks/.

The spectacular colors of fireworks are a modern innovation, and are due mostly to metal salts that are mixed in with the gunpowder. Adding strontium carbonate gives a brilliant red light, magnesium alloyed with aluminum produces a very bright white light (recall those old-fashioned camera flash bulbs; they burned magnesium), copper chloride gives out blue light. Add barium chloride for green, calcium chloride for orange and good old table salt, sodium chloride, for yellow. Iron, aluminum, and titanium dust are good for bright, silvery sparks. Zinc dust makes great smoke.

More modest and traditional skyrocket fireworks are not fired from mortars but from milk bottles, as we have seen. The business end of these stick rockets is usually a paper or pasteboard tube packed with gunpowder. When the fuse is lit, the powder is ignited. Gas is generated and whooshes out of the lower end of the tube, pushing the rocket skyward. (This is the non-technical description of rocket action—'whooshes' probably doesn't make it as a scientific descriptor.) The technical description is in Chap. 3; this physics applies to bottle rockets, *Saturn V* and everything in between.

Why rockets? Used as military and then cultural adornments from historical times, rockets became seriously important during the Cold War, we will see, as ballistic missile engines. Then rocket designs grew, flowered, stretched and extended to get humans into space during the Space Race. *This* was when rockets really grabbed the imaginations of the general public, on both sides of the Iron Curtain. Yes, rockets had been around since the year dot, but unimportantly. Yes, they became important as ICBMs, but much of that development was secret, out of the public view. But space *is* the public view, at night, and getting there became feasible with Cold War rockets. Our ancient fascination with space, and the prospect of actually sending someone there (perhaps especially the prospect of getting there ahead of either the Russians, or the Americans, depending on your Cold War camp) brought rockets and rocket development front and center. Little rockets can take a firework into the sky, so maybe big rockets could take a Yuri into space, and a Neil to the Moon.

And then... where?

Those rocket societies thrive still. They have always been relevant, but quietly faded from the bright lights of public exposure once governments and, more recently, private enterprises got interested in rockets. In the words of one recent writer, "...ordinary citizens...delighted in the great space dream, and carried rocketry during the late 1920s and into the 1930s through a network of societies."[2] Amateur space enthusiasts have put forty satellites into orbit over the past half century for amateur radio communications or as

[2] The quote is from Burrows (1998), p 64.

projects of amateur astronomers. For some of the societies, however, rocketry is the end product, not just a means to an end. Thus the Reaction Research Society, based in California, set a record for altitude achieved by a rocket developed by an amateur (George Garboden): in 1996 a rocket launched from the Black Rock Desert, Nevada, achieved an altitude of 80 km (50 miles). Another amateur group, CSXT (for Civilian Space eXploration Team), beat this and then beat it again, setting the current altitude record of 118 km in 2014.

At the other end of the scale, very small rockets (fireworks, really) cost a dollar or two. The smallest may get 5–10 m into the air. Model amateur rocketry engines are classified according to the *impulse* that they generate (impulse is thrust—the force generated by the motor—multiplied by the burn time). The class of motor is designated, in increasing size: micro, ¼A, ½A, A, B, C,... …S. The impulse increases by a factor of two each time you step up a class, so the most powerful of these amateur motors have two million times the thrust of the smallest. (Of course the professional Moonshot rockets and modern heavy-lift rockets go well beyond the thrust of even the most powerful amateur rockets—as much as 30,000 times the thrust of a class-S rocket.) Cost increases roughly proportional to impulse: you can buy a kit consisting of a rocket with a class-C motor plus launcher from Amazon for $30, whereas just the class-S motor of the CSXT *GoFast* rocket that reaches space will cost you north of $50,000. Anything up to class-G is labeled a *model rocket*, which can be purchased over the counter, and is not subject to regulation. If the motor is class-H to class-O then it propels *a high-power rocket* and is subject to government regulation in the United States, more and more so as impulse increases (Level 1 certification for class-H and -I; Level 2 for J, K, L; Level 3 for M, N, O.) American regulation (the degree of regulation varies from country to country) means a Low Explosives Users Permit, a Federal Aviation Authority (FAA) waiver, and certification that included written exams. The FAA gets a say in your high-power rocket flight because, of course, more powerful rockets fly higher (over three kilometers, or 10,000 ft) and might otherwise get in the way of overhead aircraft. The regulations, and advice about rocket construction and operation plus more technical articles than you can shake a stick at, are available from a number of national rocketry organizations, such as the two bodies that oversee high-power rocketry in the US: the National Association of Rocketry and the Tripoli Rocketry Association.[3]

[3] The National Association of Rocketry website is at www.nar.org. For the Tripoli Rocketry Association, go to www.tripoli.org. Many other countries have their own national amateur rocketry societies. The regulations governing their launches vary quite a lot from one country to the next.

Model rockets are generally powered by gunpowder propellant, but high-power rockets usually have a composite propellant, and they may be multi-stage with different propellants at each stage. All but the lowest impulse rockets are reusable—they can be recovered (typically following a parachute descent) and supplied with a new motor. Mid-to-high impulse rockets carry payloads: anything from a camera up to scientific instruments that can observe and record atmospheric or space data.[4]

Summary of the plan for this book: History, Physics, Engineering, Propulsion, Control, Guidance and finally, What's Next. Mathematical analysis is caged in an Appendix for readers who crave the physics. Our exposition is down to earth (and air and space) in that we won't shy away from gritty engineering, but will shy away from its details. We get speculative in the last chapter, where imagination becomes a reader requisite alongside a technical interest in rocket science.

Reference Works

Burrows, W.E. *This New Ocean: The Story of the First Space Age.* (New York: Random House, 1998).

Plimpton, G. *Fireworks: A History and Celebration*. (New York: Doubleday, 1984).

Werrett, S. *Fireworks: Pyrotechnic Arts and Sciences in European History*. (Chicago: University of Chicago Press, 2010).

[4] There are many Youtube videos of amateur rocket launches, covering the spectrum of rocket sizes. For low-impulse rockets that reach up to 450 m (1,500 ft) altitude, see for example the rocket competition of several enthusiastic young dudes at *Model Rocket Battle*; for more serious coverage and more powerful rockets, see *Top 5 Amateur Space Launches That Actually Worked* and *GoPro Awards: On a Rocket Launch to Space*. The latter videos show multi-stage rockets with onboard cameras.

2

History: After Fireworks Came Weapons and Spacecraft

The history of these strange machines places everything else about them in context. We will have a better idea of rocket future by knowing something of rocket past. In fact, the history of rocketry and rocketeers[1] *is very interesting anyway. So we begin our account of rocket science with its origins, both technical and intellectual (the engineering and the physics, respectively).*

The historian Arnold Toynbee once famously said that "history is just one damned thing after another." We have adopted this approach in Fig. 2.1, which presents a timeline of rocket history, setting out the key developments as a linear progression, without links. The rest of this chapter fills in the gaps, showing the links that do exist between the headlined events.[2]

To summarize this history in one paragraph: rockets were invented as a consequence of the first rocket propellant (gunpowder) being invented. Used initially as medicine and fireworks in China, the new technology quickly became adapted to warfare. Warfare then spread rocket technology across the Old World. Military applications spurred technical development, as it has in so many other fields, from metallurgy to manned flight.[3] Theoretical

[1] We prefer this term to the more traditional 'rocketmen', despite the association with Disney movies and sports cars, and despite the fact that almost all the people associated with rocket travel and development have been male, as we will see.

[2] The quote is from Toynbee (1967). See also the *Quote Investigator* article at https://quoteinvestigator.com/2015/09/16/history/ which makes clear that Toynbee was attributing this view of the contingency of history to other historians—he was critical of it.

[3] The spur of war applied to the development of manned flight is so obvious as to require no further comment from us; however the spur it provided, and no doubt continues to provide, to metallurgy perhaps should be expanded upon. Swords must be made of metal that is tough—hard but not brittle. The history of steel development is, in its early phase, very largely a history of sword technology. This development took place in different parts of the world and spread, like all good ideas. (Much of the steel for later Roman swords came from distant India, where the best steel of classical antiquity was manufactured, along the Silk Road.) See e.g. Feuerbach (2006) and Wilford (2006).

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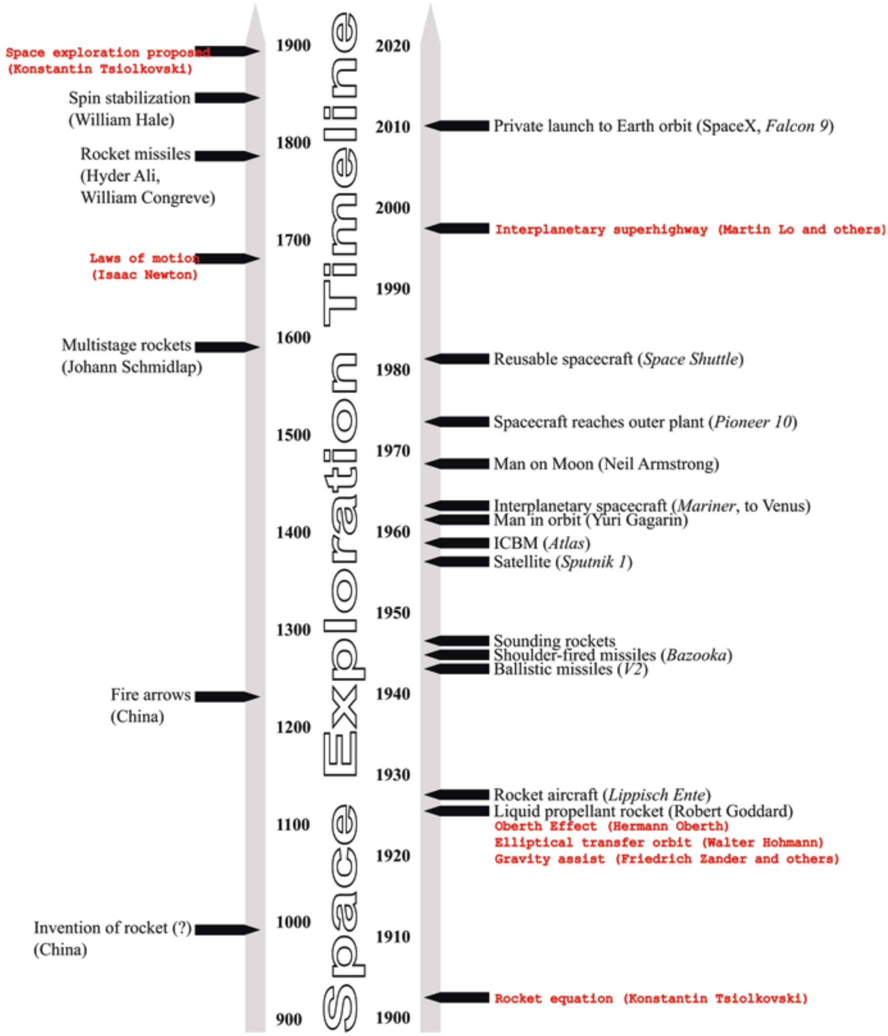

Fig. 2.1 Rocket history timeline. The left line show the major events over the first thousand years; the right line shows those of the last century or so. Different fonts are used for theoretical and practical developments.

developments in physics permitted some visionaries with a fascination for space travel to show how rockets could facilitate such travel—indeed, for reasons we will soon discuss, rockets are the only mode of powered transport in space. Thereafter the development of rocketry followed two paths: the continued application to an expanding number of increasingly important military roles, and the design and construction of vehicles for reaching space, and traveling across it.

We begin at the beginning; this approach defies the logic of many journalists (who prefer to begin with an eye-catching headline, and then backfill) and perhaps betrays our technical backgrounds. We will let you decide how much of rocket history is in the now—generated by immediate, local stimuli (the "one damned thing after another" view) and how much is interlinked, a woven pattern that threads through the centuries.

Gunpowder

It may seem odd that rocket propellant was developed before rockets, but of course the reason is clear: gunpowder was developed for other reasons, and it was only because of the existence of gunpowder than rockets *could* be invented.

A number of things in that last sentence need unpacking. First: yes, gunpowder is a rocket propellant. All we need to know about propellants in this chapter is that they are a combination of fuel and oxidizer. They contain within themselves the oxygen that they need for combustion; this characteristic distinguishes propellants from fuels. Gunpowder could burn in a vacuum (indeed, in space)—it does not need atmospheric oxygen, unlike fuels such as gasoline. Second: the name is a bad one. Gunpowder was not initially employed in guns, and when it was used in conjunction with guns it was as a grain, not a powder. To confuse things, the term has changed meaning somewhat: nowadays the word 'gunpowder' refers generically to other propellants utilized to project bullets and artillery shells; the original substance is now termed *black powder*.[4] Third: we will see that it is not clear whether rockets were invented or discovered. That is to say, they may have been a serendipitous development, an accidental discovery, rather than the result of an *Aha!* moment of some clever military engineer or fireworks technician.

Components

Gunpowder is not a pure chemical, in the sense that gasoline or nitroglycerine or baking powder or aspirin are—it is not a homogeneous material. Gunpowder is a mixture of three chemicals: two elements (sulfur S and carbon C), and a compound (potassium nitrate KNO_3) known as *saltpeter*. Sulfur is a common mineral—it is the biblical *brimstone*, and is a yellow crystalline

[4] See Denny (2011) Chapter 2, Needham (1986), Partington (1999), and Pauly (2004) Chapter 1 for more information on the naming, constitution and early application of gunpowder. The extensive Wikipedia site *Gunpowder* is reasonably comprehensive, and includes many references.

solid at room temperatures. Carbon is readily made as charcoal. These two elements are the fuel; saltpeter is the oxidizer. The proportions of these three components that are mixed together to form gunpowder varies greatly among ancient sources, and the details are important, because different mixtures produce a flammable material with different properties.

One of the older recipes[5], from Europe around 1300 CE, is for making 'flying fire' with thunder—clearly a propellant for artillery of some sort. It consists of sulfur:charcoal:saltpeter in the ratio 1:3:9. This recipe (Partington, p49) contains a higher fraction of oxidizer than some earlier recipes and is thus a better explosive. At best, gunpowder is classified as a *low explosive*, meaning that its burn rate is always subsonic (in contrast to *high explosives*, which burn supersonically). As a firearm or artillery propellant, it *deflagrates* (burns subsonically), which rapidly generates high volumes of gases (carbon dioxide and nitrogen), thus pushing the projectile musket ball or bullet or shell out of the gun barrel. It is not meant to explode so fast as to burst the chamber of the gun barrel, however, though this is a possibility if the mixture is not well matched to the gun.

The constituents of gunpowder were known a long time before they were combined. Saltpeter has been known to the Chinese for about two thousand years, as medicine. It is thought that the combination of constituents was first made for incendiary purposes in China in the ninth century, again intended as medicine. Another very early application (9–10th centuries) was for fireworks, to make an impressive display and to ward off evil spirits. One account of Chinese firework rockets dates from 1264. Modern experts are not at all unified on how or when gunpowder became an explosive, rather than a flammable material. To explode, the mixture must contain a high fraction of saltpeter and the ingredients must be mixed together intimately. The first military applications of gunpowder were for bombs and rockets; 'fire arrows' (in the sense of rocket-propelled arrows rather than arrows set alight prior to release) date from 1232 CE in the written records, though quite possibly they were in use for some time prior to being recorded. Iron barrels with chambers to contain deflagrating gunpowder came later.

[5] We need hardly say that all these early recipes for gunpowder, indeed for any chemical product from a thousand years ago, were entirely empirical. That is, the people who made gunpowder had no scientific knowledge of the ingredients, or why the recipe worked—they simply proceeded by trial and error. If a recipe worked it was kept; if fine-tuning the recipe produced a gunpowder that worked better, then the recipe was updated. This trial-and-error process (which is scientific, being based on observation and experiment) has led to great advances in many fields, from artillery to medicine. Theoretical knowledge acquired much later explains *why* the earlier trial-and-error methods worked, or didn't work, but such knowledge was not always necessary in order to gets things up and running.

Who first applied gunpowder to rockets, thus inventing rockets? Historians are unsure, but "…the real inventor of the rocket was certainly Chinese, and is sometimes said to be one Feng Jishen, who lived about 970 CE."[6]

Fire arrows

It is worth dwelling a little on these early Chinese fire arrows; they resonate with much later weapons from after the gunpowder age (which lasted six centuries, until the development of other explosives and propellants in the nineteenth century). Also, these arrows evolved into true rockets, and might just have given us our word for 'rocket', via the Chinese for 'fire arrow'.[7] The very first fire arrows were more like an artillery shell, however. From eleventh-century records it seems that they consisted of an arrow with a pouch of gunpowder attached near the arrowhead. A fuse was lit, the arrow fired from a bow and then—if the fuse timing was right—bang goes the enemy when the arrow reached its destination. Sounds more than a little hairy, but it is possible these crude devices might have been effective. They were first used in 904 CE during the siege of Yuzhang (modern Nanchang). Fire arrows that were propelled by gunpowder, rather than from an archer, may have appeared as early as 969 CE and their use is widely reported over the centuries. By the fourteenth century, the Ming army was ordering thousands of arrow rocket launchers, and may even have introduced a handheld version—a medieval bazooka.[8] The range of these rockets seems to have been greater than that of conventional arrows fired by archers, though they were nowhere near as accurate. The fire arrows were aimed by pointing the launcher in the right direction and estimating an elevation angle; fire-arrow stability in flight will have been provided by the trailing stick, much like a firework rocket. (We will have more to say about rocket stability in Chap. 5.) See Fig. 2.2.

[6] The quote is from Turner (2009), Chapter 1.

[7] According to Turner, Chapter 1. The English word for 'rocket' is often considered to be derived from an Italian word *rocchetto* meaning 'bobbin'. If so, the word was first used in 1566, according to the Oxford English Dictionary. Or in 1611 'rocket' may have come from *rocchetta*, meaning 'a small distaff', according to the Merriam-Webster online dictionary.

[8] The earlier proposed dates for the introduction of fire arrows has been disputed by Needham (1986) who points out that the contemporaneous recipes for gunpowder contained insufficient oxidizer to be used as propellant. The discussion of this section is drawn from Andrade (2016), Liang (2006) and Needham (1986). See also the Wikipedia article *Fire Arrow* and (cautiously) the NASA website *Brief History of Rockets*. The Youtube video https://www.youtube.com/watch?v=vO6I5OZpRDI is fascinating, if overly dramatized.

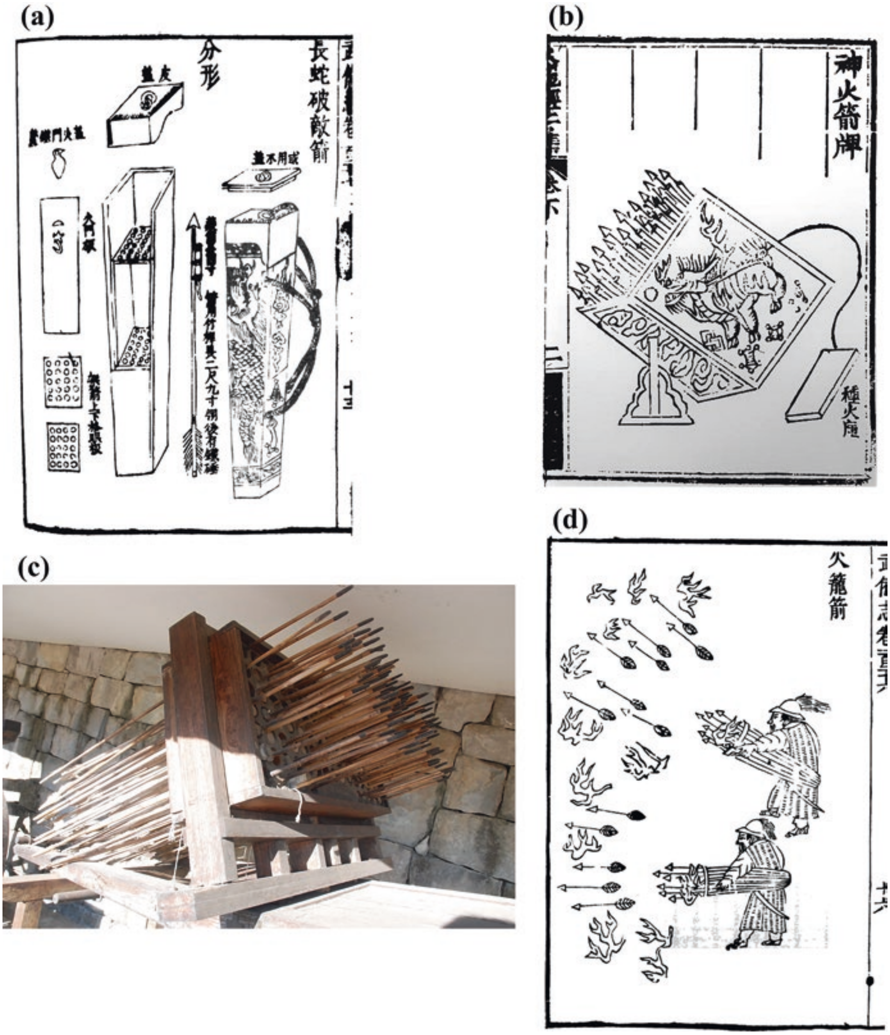

Fig. 2.2 Different configurations of fire arrows, the first rocket missiles. (a) Seventeenth-century Chinese man-portable version; this 'long serpent' launcher carried 32 poisoned arrow rockets. (b) Fourteenth-century Chinese illustration of a fire arrow rocket launcher. A box launcher like this one contained 100 arrows, which would be fired simultaneously. (c) A modern reconstruction of an early Korean multiple rocket launcher, the *hwacha* ('fire cart'). *Photo by Kang Byeong Kee.* (d) A lighter man-portable version with a basketry launcher. *Seventeenth-century Chinese illustration*.

Expanding and spreading

From the fire arrow it was but a short step to the *fire lance*. This fearsome weapon is a clear predecessor to modern firearms and flamethrowers. Here is how it worked:

- Take a charge of gunpowder, place it on the end of a long stick.
- Light the fuse, point it at a charging enemy (ahem, while holding the other end of the stick).

A variant:

- Take a fire rocket 'engine' (in other words, a rocket firework), place it on the end of a stick such that the ejected hot gases and flames point away from you.
- Light the fuse,
- Light up your approaching enemies.

The Chinese also applied gunpowder over the years to make bombs, land mines, naval mines, and bombards/ cannon. Despite attempts to keep the secret of gunpowder, knowledge of this invention—perhaps the most important one to have emerged from ancient China—spread south to India and the Korean peninsula, and north to the Mongol regions. From the Mongol expansion of the thirteenth century, knowledge of gunpowder spread westward to Persia (where its oxidizer, saltpeter, was known as 'Chinese salt'), to the Arab world (where saltpeter was called 'Chinese snow') and to Europe.

Roger Bacon, an early English philosopher and scientist, is credited with the first written reference (ca. 1267) to gunpowder made in Europe: "…a child's toy of sound and fire made in various parts of the world with powder of saltpetre, sulphur and charcoal of hazelwood."[9] This child's toy quickly turned into a weapon; in 1331 another English scholar, Walter de Milemete wrote a treatise on kingship that included illustrations of siege weapons, one

[9] The quote is from Kelly (2004). Bacon's work on gunpowder formed part 6 of his *Opus Majus*. For more on the spread of gunpowder and rockets from China to the rest of the Old World, see e.g. Denny (2011) Chapter 2, Gruntman (2004), Chapter 1, Partington (1999). In many sources the spread of rockets is frequently attested by accounts of battles, but in these accounts it is often unclear if the incendiary devices being described are rockets or some other gunpowder ordnance, such as bombs or flaming arrows (arrows set alight, as opposed to fire arrows in the Chinese sense). The much-referenced siege of Kaifeng (1232-33 CE) is a case in point.

of which was a pot-de-fer—an iron pot with a narrow neck for an arrow projectile. The pot contained gunpowder propellant, ignited via a red hot wire through a touchhole.

And so gunpowder spread around the Old World as a weapon propellant, and its application expanded over the next couple of centuries to different types of weapon (mortars, cannon, muskets, pistols) as people thought of different ways to exploit this newfangled substance. The pot-de-fer can be seen as a hybrid, a kind of missing link on the evolutionary tree of gunpowder weapon development, connecting rockets on one branch with artillery and firearms on another. The branching was an early one, and for the most part we will leave the artillery/firearm side of the tree without much further comment, as this book is concerned with the other main branch, i.e. with rocket development. The pot-de-fer is the equivalent of a feathered dinosaur, with characteristics of reptiles and birds, linking them. It fires an arrow, but is a primitive cannon—the gunpowder propellant has been moved from the projectile to the launcher. The formulation of gunpowder (the recipe) for the pot-de-fer is likely different from the fire arrow formulation, because it would have needed to burn more quickly. This brings us to the subject of *corning*, which is usually associated with firearms propellant but which we will introduce here because it brings out the important difference in deflagration rates between rockets and guns.

Corning

As with any solid propellant, gunpowder burns at its surface. This is an important characteristic that drives the design of solid-fuel rockets, as we will see. The surface area of gunpowder is greatest when the mixture of components—sulfur, carbon and saltpeter—is a fine powder. We have seen that the ingredients need to be mixed thoroughly anyway, and this is because the fuel (sulfur and carbon particles) needs to physically bind with the oxidizer (saltpeter). This binding occurs more readily when the carbon is from a porous wood, which aids the binding process at the microscopic level.[10]

So gunpowder must be a powder. But a powder deflagrates very fast—too explosively for a gun (it might burst the barrel) and too fast for a rocket.

[10] Recall that Bacon specified *hazelwood* charcoal—in fact the type of wood did make a difference in gunpowder quality due to differences in porosity. The mixing process took many hours, resulting in a powder that was as fine as talc. Our discussion about corning is taken largely from Hall (1997) pp69–74, and Partington (1999) p xxvii. These two references are very good on the early development of gunpowder weapons in Europe.

To a large extent the burning rate could be extended for rocket propellant by packing the powder in a chamber that was long and thin. Recall that gunpowder burns at its surface, so if one end is lit, and this end is the open surface of powder packed into a narrow tube, then the burn rate will be restricted. This geometrical shaping of the propellant is not enough on its own, however, for either rockets or guns. Additionally, the powder is corned—turned into grains. Corning was often done by adding a small amount of liquid (which improved the binding of ingredients), remixing and then drying. The grain size could be controlled. Larger grains correspond to a smaller total surface area, and so burn rate was controllable. Over the centuries, artillerymen (and rocketeers) learned to corn the grain to provide the best burn rate for the intended launcher.

The benefit for guns is twofold. First, an exploding powder might burst the chamber, so burn rate needed to be extended so as to reduce peak pressure. Second, an extended burn time would increase the force applied to the projectile by expanding gases. Ideally for guns, the powder would burn while the projectile was still in the barrel, with combustion being completed just as it exited. Thus, long-barreled guns should have slower-burning propellant than short-barreled weapons. Hence, propellant should be matched to gun—a one-size-fits-all approach would be both inefficient and dangerous.[11]

Rockets rise and fall

Now we can part company with guns (having noted that gunpowder has spread over much of the Old World, and has spawned a widespread and long-lasting process of artillery and then firearm development) and proceed with the development of rockets from the medieval Chinese fire arrows.

One uniquely human characteristic is our proclivity and ability to design and build machines for the sole purpose of beating the crap out of other members of our own species. Guns are perhaps the best case in point. Rockets, we like to think, have been utilized for other, higher, purposes such as fireworks, but it cannot be denied that the main spur for the development of rocket technology has been military. Fireworks became fire arrows in China; outside China the design, construction and utilization of rockets has been almost entirely for embellishing the capability and variety of weapons of war, with only a small sideline in fireworks. We are now well into the thirteenth century, and this process will continue, with ups and downs, to the

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[11] See Denny (2011) Chapter 2 for matching propellant burn rate to barrel length.

nineteenth. Rockets and guns will both spread across the Old World and diversify in design, but guns will win out so that rockets become something of an addendum to the toolkits of the world's arsenals by the sixteenth century.

In Syria around 1270–80 (after the Mongol destruction of Baghdad in 1258, which is widely regarded as ending the Islamic Golden Age), an Arab chemist and engineer named Hassan al Rammah wrote a treatise *The Book of Military Horsemanship and Ingenious War Devices*, which provided no less than 122 recipes for gunpowder, of which 22 were suitable for rocket propellant. It was likely from the Arabs that Europeans first learned of gunpowder and rockets.

A few years after the Mongol invasion of Eastern Europe in 1241, Pope Innocent IV decided that it would be a good idea to send ambassadors and other representatives to the court of the Great Khan (Gűyűk, grandson of Ghengis). One of these was a Franciscan monk, William of Rubruck (1220–93), who returned to Europe in 1257 and described his findings about all things Mongol in a very vivid account to the French king, Louis IX; within a year there are reports of experiments with gunpowder and rockets in Cologne. (Louis' soldiers would be on the receiving end of Arab rockets during the Seventh Crusade in 1268.) William's friend Roger Bacon (1214–92), whom we have already met, improved the formulation of gunpowder; the resultant was a superior propellant which increased the range of rockets. Jean Froissart (1337–1405), a French writer and historian, noted that rockets would be more accurate if launched from tubes—presaging the bazooka by some 550 years. A Bavarian military engineer, Konrad Kyeser, author of *Bellefortis* (an illustrated military manual written ca. 1405), wrote about hi-tech weaponry of the day, including counterpoise siege engines (such as the trebuchet) and rockets. An Austrian military engineer working for the Kingdom of Hungary, Conrad Haas (1509–76), described rocket technology that sounds very modern: a three-stage rocket, liquid propellant, delta-shaped stabilization fins, and even nozzles. Multistage rockets were described in a non-military context by Johann Schmidlap, a German firework maker who conducted experiments in 1590, describing a two-stage rocket. Kazimierz Siemienowicz, an artillery general in the army of the Polish-Lithuanian Commonwealth, discussed fireworks, pyrotechnics and multistage rockets in *Great Art of Artillery, Part 1* published in 1650. This work was translated into several European languages and remained a standard reference for two centuries. Nathaniel Nye, an English polymath from Birmingham, wrote *The Art of Gunnery* in 1647 based upon his experiences in the English Civil War; this book included a 43-page section on rocketry.[12]

[12] See Pacey (1991), Partington (1999), Rogers (2008), and the Wikipedia entry *Conrad Haas*.

In listing these various historical snippets regarding rockets, there is a danger for the reader of joining up dots that do not form a picture. We do not mean to imply a studied progression here; the chronological references represent independent discoveries or descriptions of different authors who may or may not have been aware of the works of others in the field. There was no planned and coordinated program to bring Europeans (or Indians or Arabs or Persians) up to speed on rocket technology—it just happened. If the result of a new idea, or propellant formulation, or launcher, was an improved weapon, then the idea spread because improved weapons get everyone's attention, whatever their culture.

Rockets became a minor part of the arsenal of armies and navies across the Old World; there are reports of rocket experimentation, tinkering, and deployment from Chinese, Indians, Arabs, Turks, Russians, Germans, Dutch, French and English over the centuries. Rocketry remained minor partly because of the limitations of propellant technology (formulations of gunpowder) and understanding about rocket engineering, but mostly because of the relatively rapid improvement in artillery. In 1687 Isaac Newton provided a sound basis for understanding the theory of rockets with his magnum opus, perhaps the most important physics book ever written.[13] Yet there were no major advances in rocketry practice until the late eighteenth century. This uptick occurred in the 1780s when troops of the British East India Company encountered Mysorean rockets.

Rockets rise redux

The British conquest of India was initially a private enterprise, not a government policy. The East India Company employed troops to reduce the various fragmented peoples of India to their rule. In the 1760s they went to war with Hyder Ali, King of Mysore in southern India. Ali and his eldest son, Tipu Sultan (one of history's more interesting characters), defended their kingdom very ably until the latter was killed at the end of the century. It took four Anglo-Mysorean wars to accomplish the subjugation of Mysore; this stout resistance was in part due to the kingdom's primacy in rocket technology.

[13] The book is *Philosophiae Naturalis Principia Mathematica* (Mathematical Principles of Natural Philosophy) known to generations of university students as *the Principia*. In it, Newton described the foundations of mechanics, which included his three laws of motion and his law of gravitation. Rockets were not discussed but, as we will see, the physics of rocketry was understood over two centuries later by applying Newton's laws of motion. Modern spacecraft trajectories are calculated using the physical principles first laid down in *the Principia*, as we will see in Chap. 3.

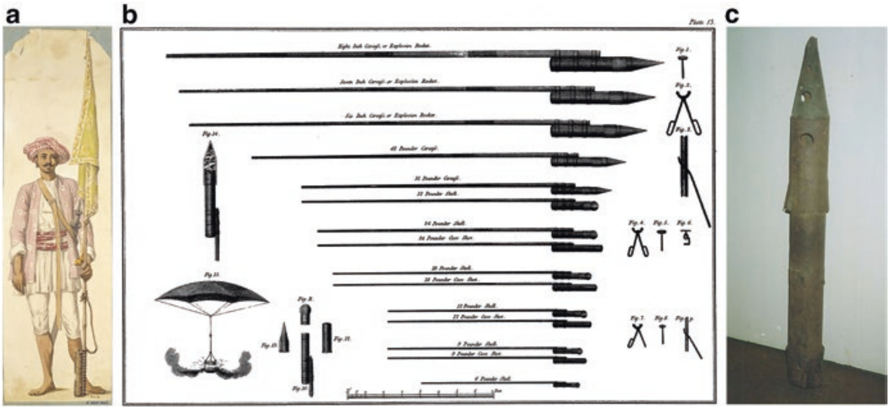

Fig. 2.3 The zenith of gunpowder war rockets. (a) A Mysore soldier uses his rocket as a flagstaff. *Watercolor by Robert Home, 1793–94*. (b) Different war rockets developed at the Woolwich Arsenal (from 1801) from rockets captured in India. *Schematic by Sir William Congreve, 1814*. (c) An 1813 example of a Congreve rocket (case—when deployed it will have been attached to a long stick) in the private collection of Hr. Klause Stolze, Leipzig. *Image by Richard Tennant*.

The Mysore army had a regular rocket corps, numbering at its peak some 5,000 men (see Fig. 2.3a). The key to their success was the soft iron tubes that encased the propellant; this tubing could withstand much higher pressures than the paper (or wood or paste board) casing of European rockets, so the rockets of Mysore had a significantly greater range—one or two kilometers. Of course they were highly inaccurate, and therefore they were fired *en masse*, to carpet a wide area. The iron case was strapped to a bamboo shaft up to 3 m (10 ft) long. Sometimes a steel blade would be attached to the trailing end of the rocket; this blade would flail around wildly due to aerodynamic instability, scything through enemy troops. Other rockets would explode overhead, like artillery shells.

Mysore rockets from this period were for many years on display in the Royal Military Depository in London.[14] Several hundred unused Mysore rockets and also rocket launchers fell into the hands of the British after the last battle (at Srirangapatam in 1799). Many were shipped back to England for analysis, thus beginning what today would be called an R&D program to

[14]Two Mysore rockets in London have the following dimensions: "(i) Casing 2.3 in. O.D. x 10 in. long (~58 mm O.D. x 254 mm long), tied with strips of hide to a straight 3 ft. 4 in. (~1.02 m) long sword blade. (ii) Casing 1.5 in. O.D. x 7.8 in. long (~37 mm O.D. x 198 mm long), tied with strips of hide to a bamboo pole 6 ft. 3 in. (~1.9 m) long." Quote from Narasimha (1985). There are Youtube videos as well as many written records about Tipu Sultan and his rockets; see e.g. https://www.youtube.com/watch?v=f-7KtJObvCE, https://www.youtube.com/watch?v=g8LkoxtsdII.

upgrade British military rockets. The result was the famous Congreve rocket, developed by Sir William Congreve, Comptroller of the Royal Laboratories at the Royal Arsenal, at Woolwich, London. At his own expense, Congreve developed modifications of the Mysore rockets and rocket propellant[15], producing a family of stick rockets from lightweights of a few pounds to heavyweights of up to 300 lb (see Fig. 2.3b, c), though those of 100 lb and up were never deployed with the British Army—they were too expensive to produce and cumbersome to transport (the sticks were up to 25 ft long). The most widely deployed Congreve rockets were the 32-pounders. Congreve standardized production and set down required specifications for propellant composition. His design allowed for two types of warhead: explosive (ball charge) or incendiary. The explosive warhead was separately ignited, with timing determined by fuse length trimmed before launch. This meant that air bursts could be implemented at set ranges.

Congreve rockets had a range of up to 9,000 ft (say 2.7 km) and were launched from a variety of rigs, some mobile and some aboard warships. They were widely employed in the war against Napoleon, with varying degrees of success. They always made an impression upon the enemy, though their inaccuracy and unreliability were a limiting factor in their adoption.

The best known use of Congreve rockets came in that sideshow to the Napoleonic war, the War of 1812, where their success and failure are well illustrated. In late August 1814 during the Battle of Bladensburg, the British 85th Light Infantry fired rockets at their American enemy, a rifle battalion commanded by the US Attorney General, with great success. Lieutenant George Gleig, a Scot who served in the campaign, witnessed the Americans response: "Never did men with arms in their hands make better use of their legs." This humiliating defeat led to the abandonment of Washington and the burning of the President's Palace (as the White House was then called).

Three weeks later during the same Chesapeake campaign, the British again fired a barrage of Congreve rockets at Fort McHenry in Baltimore. This time the rockets (32 pounders) were fired from *HMS Erebus* standing offshore. *Erebus* was a sloop that had been converted into a rocket ship, and she fired some 600–700 rockets, but they mostly fell short and failed to do significant damage to the fort. This incident is well known because it inspired a line in the US national anthem written by Francis Scott Key, who witnessed the barrage: "…And the rockets' red glare, the bombs bursting in air…", which tells us

[15] Congreve himself never acknowledged the imported Indian rockets as the source of his designs, though the influence is clear and the opportunity evident. The Mysore propellant was carefully adapted to the humid climate of southern India; Congreve adjusted the gunpowder preparation and packing in the iron casing to increase their range. See Werrett (2009).

that the warheads used on this occasion were explosive. Taken together, the two engagements show that Congreve rockets made at least a psychological impact, due to the smoke and flame, the hissing and screeching and the bursting warheads. They could do damage and break infantry formations out in the open, but not so much if they were behind fortifications. Also, *Erebus* was obliged to stand off due to the US artillery at Fort McHenry, which shows that the rockets effective range did not exceed that of artillery at the time.[16]

Congreve rockets were used by the British in most of the wars they fought during the first six decades of the nineteenth century before giving way to a new type, the spin-stabilized Hale rocket. William Hale (a British engineer) realized that canted jet vents and curved vanes would cause his rocket to spin about its direction of motion, like a rifle bullet, and that this would increase rocket stability and accuracy. It also eliminated the cumbersome sticks and eased the storage and transportation of the rockets. The range of Hale's rockets were similar to those of Congreve; the standard weight was 24 lb. Hale's invention (1844) was, interestingly, first applied by the United States Army during the Mexican-American War (1846–48), and achieved some success, particularly during the siege of Veracruz. The British Army used Hale's rockets until the end of the nineteenth century, though long before this time there had occurred significant advances in artillery technology that relegated most rockets to peacetime roles.[17]

We now consider the most important of these peacetime roles for gunpowder-propelled rockets.

Rockets to the rescue

From the beginning of the nineteenth century to the present day, there has been a long line, so to speak, of line-thrower rockets used for maritime rescues. Recently, pneumatic line throwers have replaced pyrotechnic rockets.

Shipwrecks were all too common during the Age of Sail, when onshore winds could blow these wooden vessels onto dangerous rocks during a storm. Frequently the crew and passengers of a foundering ship would be close enough to shore for their plight to be visible and audible to onlookers, but rescue by lifeboat was impossible due to raging seas and the proximity of those

[16] See Winter (2014) for the use of Congreve rockets during the War of 1812. See also Encyclopaedia Britannica online entry *Rocket and missile system* at www.britannica.com/technology/rocket-and-missile-system#ref520811. These weapons were used widely by the British and led to an increased awareness of them by the general public: in 1829 one of the first steam locomotives was named *Rocket* by its designer, Robert Stephenson.

[17] For an interesting and detailed article on the Hale rocket, see Phillips (2000).

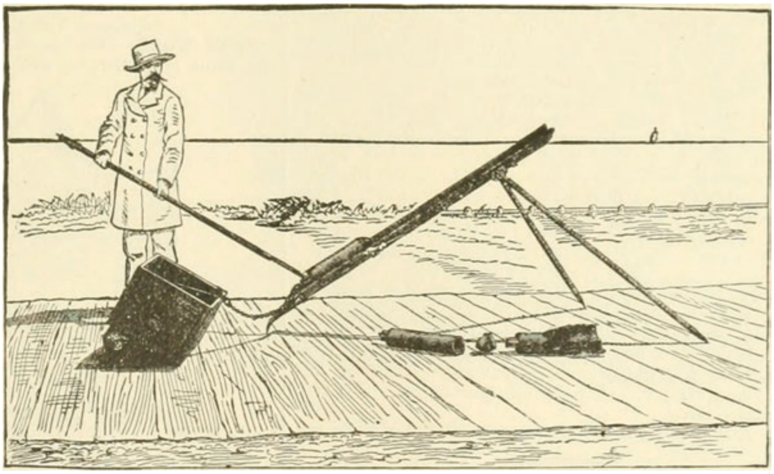

Fig. 2.4 A line-thrower rocket with line attached, for rescuing mariners from foundering ships. Illustration from *Farrow's military encyclopedia: a dictionary of military knowledge*, 1885, p68.

dangerous rocks. Enter *line throwers*, devices designed to propel a rope from shore to stricken ship, along which mariners could transit (for example via a breeches buoy or, later, a bosun's chair) to safety.

The first such device was a mortar, invented by Captain George Manby. It fired a ball that was connected to a chain or rope, and was first used to rescue seven crew of the brig *Elizabeth*, stranded off Great Yarmouth, on the south-east coast of England, in 1808. Over one thousand people are reckoned to have been saved by this device over the succeeding several decades. However, rockets were better than guns in this case, for a reason that would resonate through history, as we will see: a rocket launcher is much lighter than a gun. In 1818 Henry Trengrouse, an English engineer, developed a rocket apparatus for throwing a line over a ship in distress. Different rocket designs were utilized over the years. In 1827 a trial took place between Manby's mortar and a Trengrouse apparatus firing a rocket designed by another resident of the south coast of England, John Dennett. The rocket system (see Fig. 2.4) proved to be more effective because it was easier to maneuver over rough terrain into position opposite a foundering ship. In 1855 a simple two-stage rocket invented by Colonel Edward Boxer, of the Royal Artillery, extended the range of line throwers to perhaps 600 m and remained in use until WW2.[18]

[18] Boxer also invented the primer cap design adopted very widely for centerfire ammunition cartridges. For line-thrower history and vivid accounts of rescues, see Duncan and Gibbs (2015) and the online articles at https://www.coastguardsofyesteryear.org/articles.php?article_id=116 from the *Coastguards of*