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Further results from PIXE analysis of inks in Galileo's notes on motion

P. Del Carmine [a], L. Giuntini [a], W. Hooper [b,c], F. Lucarelli [a,d], P.A. Mandò [a,d,*]

[a] *Istituto Nazionale di Fisica Nucleare, Sezione di Firenze, Italy*
[b] *Istituto e Museo di Storia della Scienza, Firenze, Italy*
[c] *Department of History and Philosophy of Science, Indiana University, Bloomington, IN 47401, USA*
[d] *Dipartimento di Fisica dell'Università di Firenze, Firenze, Italy*

Abstract

We have recently analysed the inks in some of the folios of Vol. 72 of *Manoscritti galileiani*, kept at the Biblioteca Nazionale Centrale di Firenze, which contains a collection of loose handwritten sheets containing undated notes, data from experiments and propositions on the problems of motion from different periods of Galileo's life. This paper reports specific results obtained from the analysis of some of these propositions, which allowed to make a contribution to their chronological attribution and therefore to the solution of some historical controversies. Even in the case where the "absolute" chronological attributions could not be made on the basis of comparison with dated documents, the PIXE results provided useful information to deny or confirm the hypothesis that different propositions were written in the same or in different periods.

1. Statement of the problem

Throughout his lifetime, Galileo's ideas about natural motion evolved from traditional belongings (often vague and not experiment-based), to the modern and well-defined statements of the *Discorsi e dimostrazioni matematiche intorno a due nuove scienze*, which faithfully describe the actual physical behaviour of falling bodies. This work was published in 1638, towards the end of his life, and may be regarded as the real foundation of modern mechanics. The path through which, by means of experiments and mathematical demonstrations, Galileo reached this final settlement is recorded in a large number of undated handwritten sheets (almost 200) containing propositions, sketches of drawings, notes of experiments and calculations, which are now bound in a volume kept at the Biblioteca Nazionale Centrale di Firenze, *Ms.Gal.72*.

It is evident that the reconstruction of their chronological order is of the utmost importance for the understanding of Galileo's conceptual path towards the final settlement. This has been the object in the past few decades of a large number of studies of scholars in the history of science. A milestone in this attempt at a chronological ordering is the work of Drake [1,2], who also thoroughly studied the "material" aspects of the folios in *Ms.Gal.72*, such as style of writing (which may well change through the years), ink appearance, quality and watermark of the paper. These criteria were merged with those derived from the traditional tools of humanistic research, i.e. analysis of the contents and documentary evidence, and together allowed Drake to propose a complete scheme for the chronology of the folios or of their parts.

Some of Drake's conclusions have been questioned, however, and a number of controversies are still going on among historians of science concerning specific cases. To make a contribution to their solution, in the past two years we have undertaken a project which aims at using the composition of the inks in the folios of *Ms.Gal.72* as a criterion for chronological ordering.

The idea is to "date" the documents by a comparison of their ink composition to that of dated ones which are available, such as letters and personal notes about his financial affairs. The evidence obtained by the ink composition should always be used, of course, in conjunction with other traditional criteria.

2. Summary of previous PIXE results

The project started with a "feasibility test" on dated documents, namely letters from *Ms.Gal.14* (also from the

* Corresponding author. Dipartimento di Fisica, Università di Firenze, Largo E. Fermi 2, I-50125 Firenze, Italy. Tel.: +39 55 230 751; fax: +39 55 229 330; e-mail: mando@fi.infn.it.

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Biblioteca Nazionale Centrale di Firenze), which showed [3] that the inks used by Galileo are of the metallo-gallic type, therefore readily detectable by external PIXE in a completely nondestructive way. Upon analysis we also found that the inks in letters written within several weeks of one another exhibit very similar composition and further that the composition characteristics of one period often differed from those of inks used in other periods. This work therefore suggested that there is hope of using the ink materials as evidence for chronological ordering even though we would require a systematic survey of a considerable number of documents to establish a reasonable database for attributing "absolute" dates from such evidence.

By itself *Ms.Gal.14* only contains 98 folios and the majority of these were written either in the 1609–10 or in the 1632–42 period; some of the more interesting periods for the development of Galileo's mechanics, e.g. 1602–04 and 1618–19, are not represented in this familiar correspondence. We then addressed our interest to Galileo's financial records in *Ms.Gal.26*, covering in some detail these periods, to establish an intermediate database for the work on chronology.

In fact, a further step of the project showed that — in the presence of an adequate database for comparison — it is indeed possible to make absolute attributions of dates. Historians had long believed that f.128 of *Ms.Gal.72* was written in the autumn of 1604, since the contents of the folio linked it strongly with a letter that Galileo wrote to Fra' Paolo Sarpi in October of 1604. In addition, the watermarks on the letter and on f.128 are the same. We found [4] that the ink Galileo was using in the autumn of 1604 in the financial records (*Ms.Gal.26*) contained an unusually large amount of lead — much more than we have seen in any other sample in any collection so far. The same peculiar amounts of lead were present in f.128 of *Ms.Gal.72*. Though the lead content was probably the most striking similarity, the compositions were also similar in other respects. This result increased confidence in the validity of the PIXE-based approach to dating.

However, much work will be needed to establish a satisfactory database for comparison throughout the periods of interest for dating the folios of *Ms.Gal.72*. In any event, before an absolute chronological attribution is achieved, an important objective is what we could call "comparative dating", i.e. discrimination between the inks of the various undated documents. This is often crucial — perhaps even more than absolute dating — since most of the controversies concern just the possibility that certain notes have been written simultaneously or not. Moreover, within a single folio there may be parts written at different times, since Galileo may have come back to it even after years to make corrections or additions to the previous notes or to corroborate them with new findings.

3. New experimental results

In this paper we just give some results concerning comparative dating of documents from *Ms.Gal.72*.

So far we have examined the inks in nine of the better known folios from this collection: ff. 91v, 107v, 116v, 128, 147, 152r, 163v, 164v and 189 (v indicates that only the verso face was measured, r the recto only). Due to the limited time we had at our disposal we performed the experiments urged by curiosity to see what the inks looked like in many specific cases where controversies had arisen. This is reflected in the fact that no rigid protocol was used in carrying on the measurements: e.g. the number of ink spots examined in the various folios is largely variable. However, a number of results seem to appear even at this stage.

The measurements were performed at the KN3000 Van de Graaff accelerator in Florence, using the external-beam PIXE setup (see Fig. 1) which has been described in previous works [5]. The proton energy on the targets was 2.8 MeV and the beam currents we used were in the range of 50 to 300 pA, with a beam size of ~ 200 μm.

Also from previous experience [4,6], the characterising features for the composition of metallo-gallic inks seem to be the abundance ratios between metals, namely Fe (the most abundant in the great majority of cases), Cu, Zn, Pb and sometimes Ni.

Fig. 2 shows the Cu/Fe, Zn/Fe, Zn/Cu and Fe/Pb weight ratios as detected by PIXE in the examined ink spots, grouped by folio (or by part of a folio, when possibly different parts were present). Some general considerations can immediately be given.

(1) The dispersion of the detected ratios within the same group is in some cases large (much more than we found, e.g., in Galileo's letters, and in the many manuscripts of other kinds and ages we had examined in the course of other projects). This reflects a real variability in the ink composition from spot to spot in the same group, since the statistical uncertainties on the raw PIXE data — though nonnegligible — cannot totally account for the detected dispersion. We must admit that we do not fully understand such a variability — note that it is not always to the same degree — and to clarify these points, we are actively engaged in other collaborations directed at understanding the physico-chemical behaviour of the metallo-gallic inks and of their interactions with paper.

(2) In spite of this large dispersion, remarkable and significant differences are observed among the examined documents, so that some chronological associations can be proposed. In particular, at least for this group of documents, it is from the Cu/Fe, Pb/Fe and Zn/Cu ratios that a differentiation can be obtained, while the Zn/Fe ratio does not seem to carry any significant contribution to differentiating between groups.

Let us focus on some specific problems.

Folio 152r was first discussed by Drake [7] who believed that it recorded Galileo's discovery of the time-squared law, circa 1604, and associated f.152r closely with f.128. However, in the latter folio, the correct conclusion (s is proportional to t^2 in the free fall from rest), is derived from a mistaken assumption (v is proportional to s rather than to t), that he later corrected; on the contrary, as argued by Hooper [8], f.152r seems to record the discovery of the correct law of speeds (as reported in the final settlement of the *Due nuove scienze*), the foundation of Galileo's theory of parabolic trajectories. Therefore, f.152r should be dated later than f.128 and should be closely related in particular to f.91v, also containing drafts of the basic theorems on parabolic trajectories, and especially the law of speeds. Drake had believed instead that f.91v was composed three years after f.152r (and f128).

If we extract what concerns these three folios from Fig. 2, it is apparent that Drake's hypothesis is undermined by the ink composition data. As is shown in Fig. 3, not only are all the three considered ratios completely different in f.152r and f.128, but the experimental data show a remarkable similarity between f.91v and f.152r, thus supporting their chronological association.

Another result in attribution of relative chronology concerns f.163, f.164v, f.189 and f.116v.

Folio 163 explicitly states the mistaken principle found on f.128 (uncorrect law of speeds, see above). Arguing from an analogy with uniform motion, the second proposition on f.164v attempts to demonstrate that bodies accelerate to the same speed ("velocitas") when they fall through the same height regardless of the inclinations of their paths (Fig. 1 shows a photograph of this folio while being analysed under beam). The second proposition does not consider the relation between velocities acquired at different heights, but the ideas expressed in this proposition play a central role in another discussion of the incorrect law of speeds. The third proposition on f.164v (written by the way in an ink of an apparently different shade) clearly states the correct law of speeds. Thus the question arises whether the third proposition was written in the same period as the second or was added at a later date. Drake

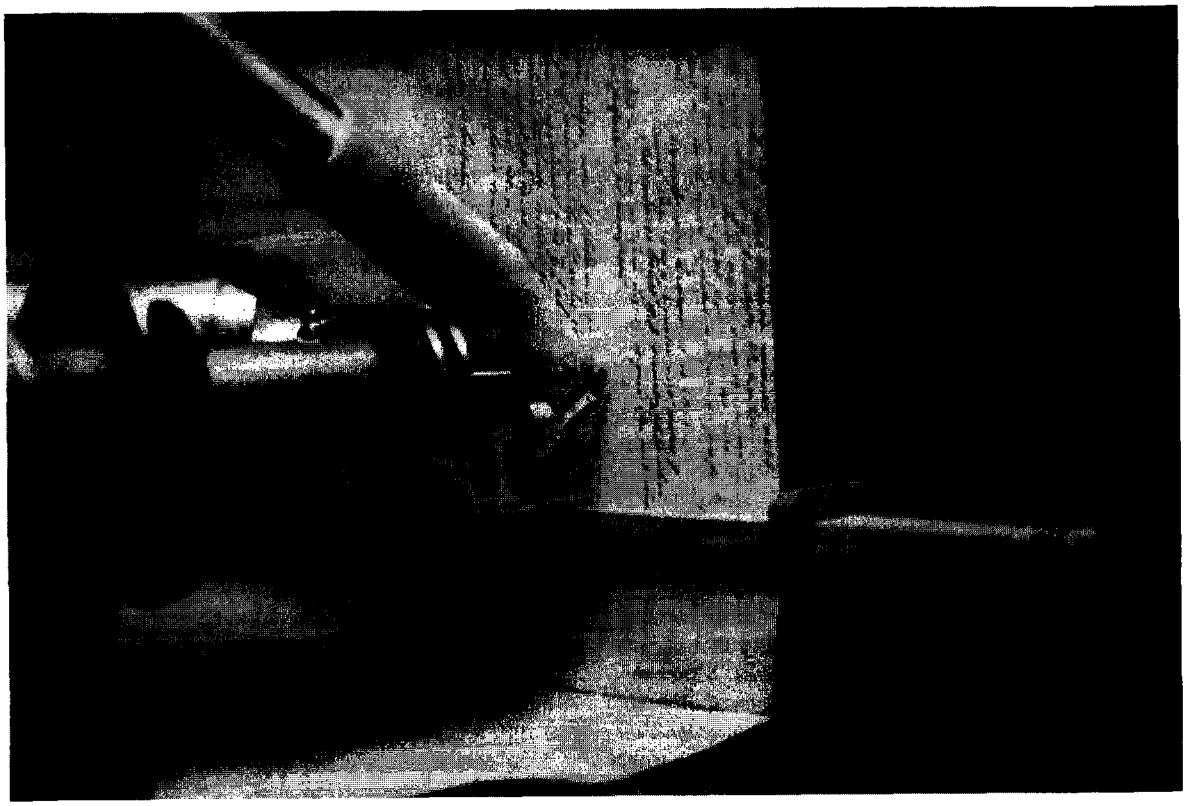

Fig. 1. Folio 164v of Vol. 72 (*Mss. Galileiani*) during analysis in the external-beam setup at our Laboratory. PIXE-based ink composition data strongly support the hypothesis that the third proposition (last two lines, "Momenta velocitatis ...") has been added later by Galileo.

maintained that the last two propositions of f.164v were written together in 1607; Hooper has suggested [8] that the second proposition may have been written as early as 1603–04 while the third was added perhaps as late as 1608–09.

Folios 189 and 116v record experiments, respectively, on the descent along the chords of a vertically erect circle and on parabolic trajectories that were performed with an actual apparatus, and carry notes which let us understand that while performing these experiments Galileo was already in possession of the correct law of speeds. From this and further evidence it had been argued [8] that they might be chronologically associated with the last proposition of f.164v.

Now, if we extract from Fig. 2 the data concerning this group of folios (Fig. 4), striking evidence is first obtained

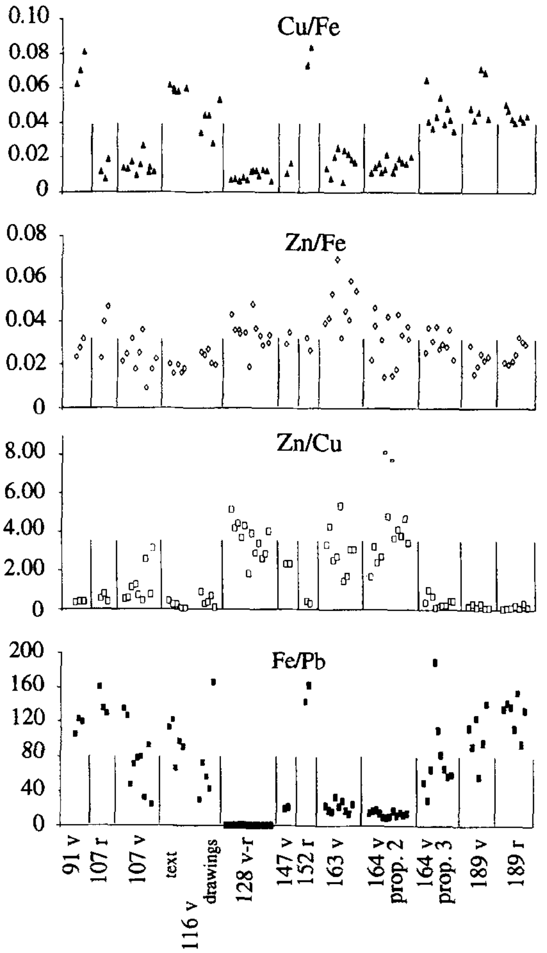

Fig. 2. From top to bottom, Cu/Fe, Zn/Fe, Zn/Cu and Fe/Pb weight ratios detected in the examined ink spots, grouped by folio (or by part of a folio when different parts are present).

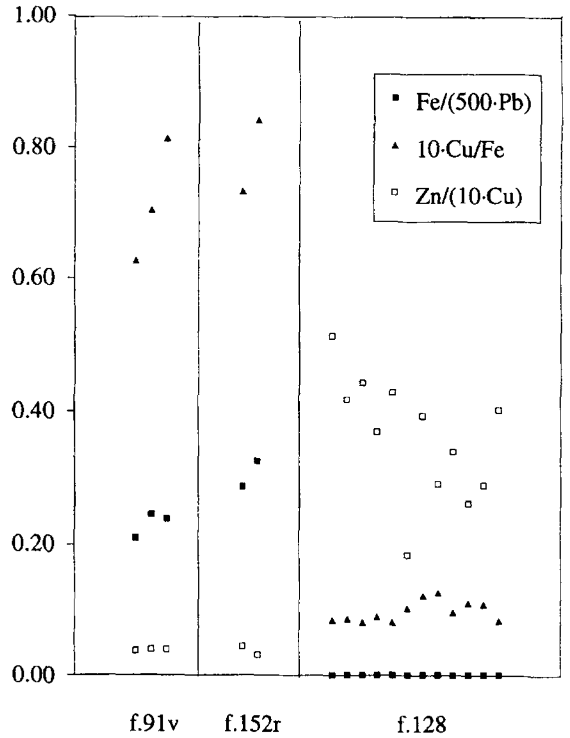

Fig. 3. Fe/Pb, Cu/Fe and Zn/Cu weight ratios detected in the examined ink spots of folios 91v, 152r and 128. The ratios are multiplied by appropriate factors for graphical evidence.

for the difference between the inks of the second and third proposition of f.164v: all the considered ratios are remarkably different (preliminary results concerning fewer measurements on this folio had been given in Ref. [3]). In addition, these data reinforce the proposed association of f.163 to the second proposition of f.164v and that of the third proposition of f.164v to f.189 and f.116v.

4. Final remarks

In general, while the ink composition data can be a "strong" argument to deny a close chronological association, more caution should be exercised in their use as arguments in positivo, at least until a much more detailed database is available from safely dated documents.

We are conscious of the fact that a lot of work still remains to be done, together with the community of historians of science; we feel encouraged, however, by these first results, which indeed appear to have contributed to a clarification of some controversial chronologies.

We do hope to be allowed to proceed with the project by analysing many further documents, both dated and undated. Any collaboration and, in particular, contributions

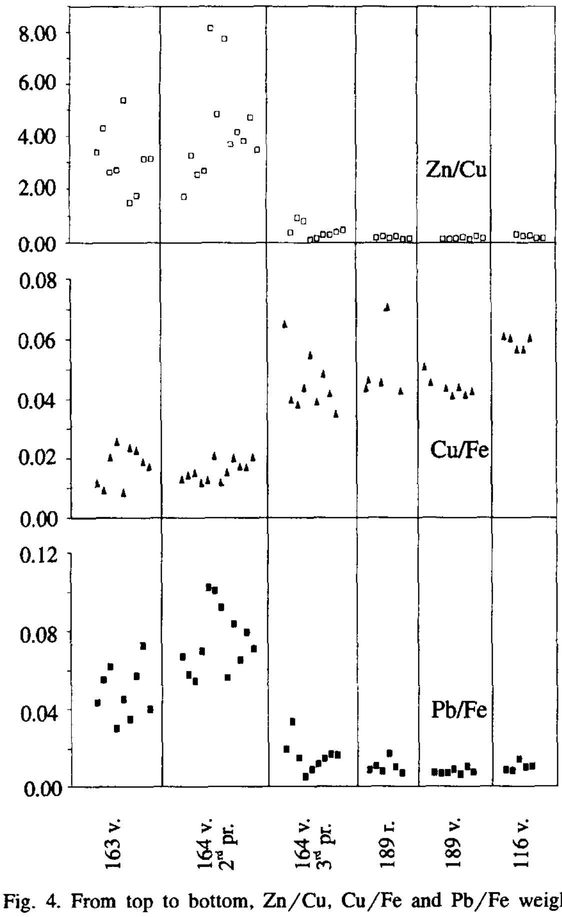

Fig. 4. From top to bottom, Zn/Cu, Cu/Fe and Pb/Fe weight ratios detected in the examined ink spots of folios 163v, 164v 2nd and 3rd propositions, 189r, 189v and 116v.

to a clarification of the large dispersions sometimes observed in the compositional data will be welcome.

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