CORRECTED VERSION OF ”BOUNDARY VOLUME AND LENGTH SPECTRA OF RIEMANNIAN MANIFOLDS: WHAT THE MIDDLE DEGREE HODGE SPECTRUM DOESN’T REVEAL”

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Abstract. Let \( M \) be a \( 2m \)-dimensional compact Riemannian manifold. The article [GR] “Boundary volume and length spectra of Riemannian manifolds: What the middle degree Hodge spectrum doesn’t reveal” showed that the spectrum of the Hodge Laplacian acting on \( m \)-forms does not determine whether the manifold has boundary, nor does it determine the lengths of the closed geodesics. Among the many examples are a projective space and a hemisphere that have the same Hodge spectrum on 1-forms, and hyperbolic surfaces, mutually isospectral on 1-forms, with different injectivity radii. Moreover, the Hodge \( m \)-spectrum also does not distinguish orbifolds from manifolds. We correct an error in one of the examples. In addition, the article asserted that if a Riemannian orbifold \( O \) with singularities and a Riemannian manifold \( N \) share a common Riemannian cover, then they can be distinguished by the spectra of their Laplace-Beltrami operators acting on functions. We correct this statement by requiring that the common cover \( M \) be either compact or Riemannian homogeneous.

In what follows, we have inserted the corrections and small addenda to the original article [GR] in blue. The errata will appear in Ann. Inst. Fourier, Grenoble.

To what extent does spectral data associated with the Hodge Laplacian \( dd^* + d^*d \) on a compact Riemannian manifold \( M \) determine the geometry and topology of \( M \)? Let \( \text{spec}_p(M) \) denote the spectrum of the Hodge Laplacian acting on the space of \( p \)-forms on \( M \), with absolute boundary conditions in case the boundary of \( M \) is non-empty.

\textbf{Key words and phrases.} Spectral geometry, Hodge Laplacian, isospectral manifolds, heat invariants

\textbf{Mots Clés.} Géométrie spectrale, laplacien de Hodge, variétés isospectrales, invariants de la chaleur.

\textit{2000 Mathematics Subject Classification.} Primary 58J53; Secondary 53C20.

The first author is partially supported by a grant from the National Science Foundation. The second author is partially supported by Conicet.
(We will review the notion of absolute and relative boundary conditions in Section 1.) For each $p$, the spectrum $\text{spec}_p(M)$ is known to contain considerable geometric information. For example, under genericity conditions, the $p$-spectrum of a closed Riemannian manifold $M$ determines the geodesic length spectrum of $M$.

In this article, we will focus on even-dimensional manifolds and give a very simple method for obtaining manifolds with the same Hodge spectrum in the middle degree. Through examples, we will discover that this middle degree spectrum contains a perhaps surprising lack of topological and geometric information.

Among the examples of manifolds that we will construct with the same middle degree spectrum are:

- a cylinder, a Möbius strip, and a Klein bottle;
- pairs of cylinders with different boundary lengths;
- a hemisphere and a projective space;
- products $S(r) \times P(s)$ and $P(r) \times S(s)$, where $P(t)$, respectively $S(t)$, denote a projective space, respectively sphere, of radius $t$ (for generic $r$ and $s$, the length spectra differ);
- non-orientable closed hyperbolic surfaces with different injectivity radius and length spectrum;
- pairs of surfaces, one with an arbitrarily large number of boundary components and the other closed. The metrics can be chosen to be hyperbolic.

We also obtain examples in all even dimensions exhibiting similar properties.

These examples prove:

**Theorem.** The middle degree Hodge spectrum of an even-dimensional Riemannian manifold $M$ does not determine:

(i) the volume of the boundary or even whether $M$ has boundary;
(ii) the geodesic length spectrum or injectivity radius. In particular, it does not determine the length of the shortest closed geodesic.

The result (i) is new. Concerning (ii), R. Miatello and the second author [MR3] recently constructed examples of flat manifolds, $p$-isospectral for various choices of $p$, such that the length of the shortest closed geodesic differed. (Here, we say two manifolds are $p$-isospectral if they have the same $p$-spectrum.)

Note that all the closed manifolds that we construct are non-orientable. For orientable surfaces, the 1-spectrum completely determines the 0-spectrum (which coincides with the 2-spectrum). Thus the behavior
exhibited by our examples cannot occur for 1-isospectral orientable surfaces. For non-orientable surfaces, the 0-spectrum and 2-spectrum no longer coincide and the 1-spectrum is the join of the two (except for the 0-eigenspace). Our examples show that the join of the two spectra contains less geometric information than either one individually. In higher dimensions, it is perhaps surprising that all our examples are non-orientable. The Hodge \( \ast \) operator intertwines the exact and co-exact middle degree forms and commutes with the Laplacian; thus the “exact” and “co-exact spectra” coincide. Hence the \( m \)-spectrum of a \( 2m \)-dimensional orientable closed manifold, \( m > 1 \), contains half the information contained in the \( (m - 1) \)-spectrum and nothing more (except for the dimension of the space of harmonic forms). In contrast, for non-orientable manifolds, the “exact” and “co-exact spectra” no longer coincide, so the middle degree spectrum ostensibly contains the same amount of data as the other spectra.

One of the primary tools for recovering geometric and topological information from the spectra is through the small time asymptotics of the heat equation. See, for example, [Gi] or [BBG1], [BBG2]. For closed manifolds, the trace of the heat kernel associated with the Hodge Laplacian on \( p \)-forms has an asymptotic expansion of the form

\[ \zeta(t) = (4\pi t)^{-n/2}(a_0(p) + a_1(p)t + a_2(p)t^2 + \ldots). \]

The coefficients \( a_i(p) \) are spectral invariants and are given by integrals, with respect to the Riemannian measure, of expressions involving the curvature and its covariant derivatives. The first three heat invariants are given as follows: \( a_0 = C_0(p)\text{vol}(M) \); \( a_1(p) = C_1(p)\int_M \tau \), where \( \tau \) is the scalar curvature and \( C_i(p) \), \( i = 1, 2 \), is a constant depending only on \( p \); and \( a_2(p) \) is a linear combination, with coefficients depending only on \( p \), of \( \int_M \tau^2 \), \( \int_M \|\text{Ric}\|^2 \) and \( \int_M \|R\|^2 \).

For manifolds with boundary, the expansion is instead in powers of \( t^{\frac{1}{2}} \). The coefficient \( a_{\frac{1}{2}}(p) \) is given by \( c(p)\text{vol}(\partial M) \), where \( c(p) = \binom{n-1}{p} - \binom{n-1}{p-1} \).

A very difficult open question is whether the heat invariants are the only integral invariants of the spectrum, i.e., the only invariants which are integrals of curvature expressions either over the manifold or over the boundary. This article and work of Dorothee Schueth lend support (albeit in a small way) towards an affirmative answer since:

- The coefficient \( a_{\frac{1}{2}}(p) = c(p)\text{vol}(\partial M) \) vanishes precisely when \( \dim(M) \) is even and \( p = \frac{1}{2} \dim(M) \). Our examples show in this case that the \( p \)-spectrum indeed does not determine the volume of the boundary.
Dorothee Schueth showed that the three individual integral terms in the expression for $a_2(0)$ are not spectral invariants.

A secondary theme of this paper is the spectrum of Riemannian orbifolds. Riemannian orbifolds are analogs of Riemannian manifolds but with singularities. They are locally modelled on quotients of Riemannian manifolds by finite effective isometric group actions. The singularities in the orbifold correspond to the singular orbits. One can define the notion of Laplacian on $p$-forms on orbifolds. A natural question is whether the spectrum contains information about the singularities. We will see:

**Theorem.** The middle degree Hodge spectrum cannot distinguish Riemannian manifolds from Riemannian orbifolds with singularities.

For example, in dimension $2m$, $m > 1$, we will construct spherical orbifolds with singular sets of arbitrary odd dimension that are $m$-isospectral to a projective space and to a hemisphere. We will similarly construct flat orbifolds of dimension $2m$, $m > 1$ that are isospectral to flat manifolds. To our knowledge, the examples given here are the first examples of orbifolds $p$-isospectral to manifolds for some $p$. In the original version of this article, we also asserted that the mutually 1-isospectral cylinder, Klein bottle and Möbius strip are 1-isospectral to a “pillow”, a 2-dimensional orbifold with four singular points. However, this is incorrect; as we will explain in Proposition 3.1, the eigenvalue zero occurs in the 1-spectrum of the cylinder, Klein bottle and Möbius strip but not in the 1-spectrum of the pillow. (The spectra agree otherwise.) We do not know whether the spectrum of the Laplacian on functions can distinguish orbifolds from manifolds, although we will give some positive results in §3 with corrections and we will verify that none of the middle degree isospectral orbifolds and manifolds we construct are 0-isospectral.

We will also construct orbifolds, isospectral in the middle degree, having singular sets of arbitrarily different dimensions.

In this paper we have concentrated on $m$-isospectrality of $2m$-manifolds and orbifolds. However, for various choices of $p$, one can also obtain $p$-isospectral orbifolds with singular sets of different dimensions. This phenomenon may be discussed in a later paper.

We conclude these introductory remarks with a partial history of the isospectral problem for the Hodge Laplacian. For a general survey of isospectral manifolds, see [Go3]. Most known examples of isospectral manifolds, e.g., those constructed by the method of Sunada [Sun], are strongly isospectral; in particular, the manifolds are $p$-isospectral for all $p$. Thus they do not reveal possible differences in the geometric
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information contained in the various $p$-spectra. The article [Go1] gave the first example of 0-isospectral manifolds which are not 1-isospectral; further examples were given in [Gt1], [Gt2]. (The 0-spectrum, i.e., the spectrum of the Laplacian acting on smooth functions, is frequently referred to simply as the spectrum of the manifold.) Ikeda [Ik] constructed, for each positive integer $k$, spherical space forms which are $p$-isospectral for all $p$ less than $k$ but not for $p = k$. In the past decade, many examples have been constructed of 0-isospectral manifolds with different local as well as global geometry, e.g. [Sz1], [Sz2], [Go2], [Go4], [GW], [GGSWW], [GSz], [S1], [S2], [S3], and [Gt1]; at least in those cases in which comparisons of the higher $p$-spectra have been carried out, these manifolds are not $p$-isospectral for $p \geq 1$. The first examples of manifolds which are $p$-isospectral for some values of $p$ but not for $p = 0$ were flat manifolds constructed by R. Miatello and the second author in [MR1], [MR2], [MR3]. R. Gornet and J. McGowan (private communication) recently constructed examples of spherical space forms which are simultaneously $p$-isospectral for $p = 0$ and for various other, but not all, $p$.

The second author wishes to thank the mathematics department at Dartmouth College for its great hospitality during the time this paper was written.

1. Method for Constructing Manifolds Isospectral in the Middle Degree

1.1. Definition. Suppose $M$ is a compact Riemannian manifold with boundary. Let $\omega$ be a smooth $p$-form on $M$. For $x \in \partial M$, write

$$\omega_x = \omega^T_x + \omega^N_x,$$

where $\omega^T_x \in \bigwedge^p(\partial M)^*_x$ and $\omega^N_x = \sigma \wedge \mu$ with $\sigma \in \bigwedge^{p-1}(\partial M)_x^*$ and $\mu$ a vector in $T_x^*(M)$ normal to the cotangent space of $\partial M$ at $x$. The form $\omega$ is said to satisfy absolute, respectively relative, boundary conditions if $\omega^N = 0 = (d\omega)^N$, respectively $\omega^T = 0 = (\delta\omega)^T$, everywhere on $\partial M$. If $M$ is orientable, observe that $\omega$ satisfies the relative boundary conditions if and only if $*\omega$ satisfies the absolute boundary conditions, where $*$ is the Hodge duality operator.

1.2. Notation and Remarks. Let $M$ be a compact Riemannian manifold of dimension $n = 2m$.

(i) If $M$ is closed let $\text{spec}_m(M)$ denote the spectrum of the Hodge Laplacian of $M$ acting on smooth $m$-forms.

(ii) If $M$ has boundary, we denote by $\text{spec}_m(M)$ the absolute spectrum of $M$. If $M$ is orientable, then since the Hodge $*$ operator carries $\mathcal{A}^m(M)$ to itself and commutes with the Hodge Laplacian, we see
from 1.1 that the absolute $m$-spectrum coincides with the relative $m$-spectrum. However, this coincidence of the spectra does not in general occur when $M$ is non-orientable.

(iii) Suppose that $M$ is closed and $\tau$ is an orientation reversing isometric involution. If $\tau$ does not act freely, then $\langle \tau \rangle \setminus M$ is a Riemannian orbifold. Its $m$-spectrum is defined to be the spectrum of the Hodge Laplacian of $M$ acting on the space of $\tau$-invariant $m$-forms. We denote this spectrum by $\text{spec}_m(\langle \tau \rangle \setminus M)$. (In this article we will be concerned only with orbifolds of this form. For a more general discussion of orbifolds, see for example [Sc] or [T].)

If the fixed point set of $\tau$ is a submanifold of codimension one, then the underlying space of the orbifold $\langle \tau \rangle \setminus M$ is a Riemannian manifold with boundary. The boundary corresponds to the singular set of the orbifold. (E.g., if $M$ is a sphere and $\tau$ is reflection across the equator, then $\langle \tau \rangle \setminus M$ is an orbifold whose underlying space is a hemisphere.)

Since the orbifold $m$-spectrum $\text{spec}_m(\langle \tau \rangle \setminus M)$ just defined agrees with the $m$-spectrum of the underlying manifold with absolute boundary conditions, we will ignore the orbifold structure and view $\langle \tau \rangle \setminus M$ as a manifold with boundary in what follows. This point of view allows us to obtain manifolds with boundary as quotients of closed manifolds.

1.3. Theorem. Let $M$ be a $(2m)$-dimensional orientable closed Riemannian manifold. Suppose that $\tau$ is an orientation reversing involutive isometry of $M$. Then $\text{spec}_m(\langle \tau \rangle \setminus M)$ consists precisely of the eigenvalues of $\text{spec}_m(M)$ but with all multiplicities multiplied by $\frac{1}{2}$.

Proof. Let $\lambda$ be an eigenvalue in $\text{spec}_m(M)$, say of multiplicity $m_\lambda$. Both $\tau$ and the Hodge $*$ operator commute with the Hodge Laplacian and thus leave the $\lambda$-eigenspace $H_\lambda \subset A^m(M)$ invariant. Letting $H^\lambda_+$, respectively $H^-\lambda$, denote the space of $\tau$-invariant, respectively $\tau$-anti-invariant, forms in $H_\lambda$, then $H_\lambda = H^\lambda_+ \oplus H^-\lambda$. The $\lambda$-eigenspace in $A^m(\langle \tau \rangle \setminus M)$ corresponds to $H^\lambda_+$.

The Hodge $*$ operator interchanges $H^\lambda_+$ and $H^-\lambda$. To see this, let $\Omega$ denote the Riemannian volume form of $M$. For $\alpha \in A^m(M)$, we have $\alpha \land *\alpha = \|\alpha\|^2\Omega$ and $\tau^*\alpha \land \tau^*(\alpha) = \|\alpha\|^2\tau^*\Omega = -\|\alpha\|^2\Omega$, since $\tau$ is an orientation reversing isometry. Thus $*$ interchanges $H^\lambda_+$ and $H^-\lambda$.

Consequently, $H^\lambda_+$ and $H^-\lambda$ both have dimension $\frac{1}{2}m_\lambda$, and the theorem follows.

1.4. Corollary. Let $M_1$ and $M_2$ be $(2m)$-dimensional orientable closed Riemannian manifolds with $\text{spec}_m(M_1) = \text{spec}_m(M_2)$. Suppose that $\tau_1$ and $\tau_2$ are orientation reversing involutive isometries of $M_1$ and $M_2$,
respectively. Then
\[ \text{spec}_m(\langle \tau_1 \rangle \backslash M_1) = \text{spec}_m(\langle \tau_2 \rangle \backslash M_2). \]
Moreover, if \( N \) is a \( 2k \)-dimensional closed Riemannian manifold, then
\[ \text{spec}_{m+k}(\langle \tau_1 \rangle \backslash M_1) \times N = \text{spec}_{m+k}(\langle \tau_2 \rangle \backslash M_2) \times N. \]

For the second statement, observe that \( \tau_i \) extends to an involutive orientation reversing isometry of \( M_i \times N \).

**Remark.** The conclusion fails to hold if we drop the hypothesis that the involutions be orientation reversing. For example, let \( M_1 = M_2 = \mathbb{Z} \times 2\mathbb{Z} \setminus \mathbb{R}^2 \), and let \( \tau_1 \) and \( \tau_2 \) be the translations \((x, y) \mapsto (x + \frac{1}{2}, y)\) and \((x, y) \mapsto (x, y + 1)\), respectively. Then the quotient tori are not 1-isospectral.

In our applications of Corollary 1.4 below, we will take \( M_1 = M_2 \).

A useful special case of Corollary 1.4 is the following:

1.5. **Corollary.** Let \( M \) and \( M' \) be manifolds of dimension \( k \) and \( k' \), respectively, with \( k + k' \) even, say \( k + k' = 2m \). Suppose \( \phi \) and \( \phi' \) are orientation reversing involutive isometries of \( M \) and \( M' \) respectively. Then \( \langle \phi \rangle \backslash M \times M' \) is \( m \)-isospectral to \( M \times \langle \phi' \rangle \backslash M' \).

Given a Riemannian manifold \( M \) and a non-negative integer \( k \leq \dim(M) \), let \( \{\lambda_j\}_{j=1}^{\infty} \) be the spectrum of the Laplacian acting on \( k \)-forms on \( M \). The complexified heat trace is given by \( Z(z) = \sum_{n=0}^{\infty} \exp(-\frac{\lambda_n}{z}) \) for \( z \in \mathbb{C} \). Recall that Y. Colin de Verdière [C] obtained an expansion of the complexified heat trace as a sum of oscillating terms whose periods are related to the lengths of the closed geodesics in \( M \). The authors are grateful to the referee for pointing out the following additional corollary of Theorem 1.3.

1.6. **Corollary.** Suppose that \( N \) is a nonorientable closed Riemannian manifold of dimension \( 2m \). Let \( \gamma \) be an isolated, nondegenerate simple closed geodesic such that the holonomy about \( \gamma \) is orientation reversing. Then \( \gamma \) does not contribute to the complexified heat trace associated with the Laplacian acting on \( m \)-forms.

**Proof.** Let \( M \) be the orientation covering of \( N \) with the lifted Riemannian metric. By Theorem 1.3, the complexified heat traces of \( M \) and \( N \) associated with the Laplacian on \( m \)-forms coincide except for a factor of \( \frac{1}{2} \). Since the lift of \( \gamma \) to \( M \) is not closed, it does not contribute to the complexified heat trace of \( M \) and hence \( \gamma \) does not contribute to that of \( N \). \( \square \)
1.7. **Remark.** In the setting of Corollary 1.6 with $m = 1$, it was already known that the contribution of $\gamma$ to the complexified heat trace on 1-forms must be zero up to principal order since the principal order coefficient is the trace of the holonomy map about the geodesic.

2. **Examples of manifolds isospectral in the middle degree**

2.1. **Remark.** Most, though not all, of the examples we construct below will be surfaces. However, by taking products of the manifolds in these examples with a closed manifold $N$ and applying the second statement of Corollary 1.4, one obtains examples in arbitrary even dimensions.

We begin with manifolds of positive curvature.

2.2. **Hemispheres and projective spaces.** Let $M$ be the $(2m)$-sphere, $m \geq 1$, let $\tau$ denote the antipodal map and let $\sigma$ denote reflection about an equatorial sphere. Then Corollary 1.4 implies that the projective space $\langle \tau \rangle \setminus M$ is $m$-isospectral to the hemisphere $\langle \sigma \rangle \setminus M$. (I.e., the $m$-spectrum of the projective space coincides with the absolute $m$-spectrum of the hemisphere.)

2.3. **Half ellipsoids with different boundary volume.** Let $M$ be a $2m$-dimensional ellipsoid (not round) and let $\sigma$ and $\tau$ denote the reflections across two different hyperplanes of symmetry. Then $\langle \tau \rangle \setminus M$ and $\langle \sigma \rangle \setminus M$ are $m$-isospectral manifolds with boundary, but their boundaries have different volume.

2.4. **Products of spheres and projective spaces with different length spectra and injectivity radius** Let $S^k(r)$ and $P^k(r)$ denote the sphere and projective space, respectively, of radius $r$ and dimension $k$. Then by Corollary 1.5, for $m, n \geq 1$ and for any $r, s > 0$, the manifolds $S^{2m}(r) \times P^{2n}(s)$ and $P^{2m}(r) \times S^{2n}(s)$ have the same $(m+n)$-spectrum. However, for generic choices of $r$ and $s$, the lengths of the shortest closed geodesics in the two manifolds differ.

These closed manifolds are also isospectral to the product of a hemisphere and a sphere, as can be seen by taking an involution of $S^{2m}(r) \times S^{2n}(s)$ given by the equatorial reflection in one factor.

We next consider flat manifolds.

2.5. **Cylinders, Klein bottles, and Möbius strips.** The following, with appropriately chosen sizes, are mutually 1-isospectral:

(i) a Klein bottle;
(ii) a cylinder, say of perimeter $p$;
(iii) a Möbius strip of perimeter $\frac{p}{\sqrt{2}}$.

Indeed each of these is a quotient of $T = \mathbb{Z}^2 \backslash \mathbb{R}^2$ by an involution $\tau$ arising from an involution $\tilde{\tau}$ of $\mathbb{R}^2$ given as follows: For the Klein bottle, $\tilde{\tau}$ is the composition of translation by $(\frac{1}{2}, 0)$ with reflection $R$ about the $x$-axis. For the cylinder, $\tilde{\tau}$ is the reflection $R$ just defined. For the Möbius strip, $\tilde{\tau}$ is reflection across the line $x = y$.

Thus by Corollary 1.4, the Klein bottle, the cylinder and the Möbius strip all have the same 1-form spectrum.

2.6. Cylinders of different shapes. Let $C_{(h,w)}$ denote the flat cylinder of height $h$ and circumference $w$, hence of perimeter $2w$. Then for all $a, b > 0$, we have

$$\text{spec}_1(C_{(a,\frac{h}{2})}) = \text{spec}_1(C_{(b,\frac{w}{2})})$$

since both cylinders are quotients by a reflection of a rectangular torus of height $a$ and width $b$. Thus cylinders of arbitrarily different perimeters can have the same 1-form spectrum.

2.7. Remarks. (i) One similarly obtains pairs of non-isometric Klein bottles with the same 1-spectra and with different lengths of closed geodesics.

(ii) By taking $M$ to be a rhomboidal torus and letting $\tau_1$ and $\tau_2$ be reflections across the “diagonals” one similarly obtains pairs of 1-isospectral Möbius strips of arbitrarily different perimeters.

(iii) By taking products of the various 1-isospectral flat manifolds in 2.5, 2.6 and in these remarks with a torus of dimension $2m - 2$ and recalling Remark 2.1, we obtain pairs of $m$-isospectral $2m$-dimensional flat manifolds with the same boundary behavior as the surfaces in these examples.

Finally we consider hyperbolic surfaces.

2.8. Theorem. In each genus $g > 1$, there exist non-orientable hyperbolic closed surfaces $S_1, S_2, S_3,$ and $S_4$ of genus $g$ such that:

(a) All four surfaces have the same Hodge spectrum on 1-forms;
(b) They have different length spectra (different in the strong sense that different lengths occur, not just different multiplicities), and $S_4$ has a smaller injectivity radius than $S_1, S_2,$ and $S_3$.
(c) The Laplacians acting on functions on these surfaces are not isospectral.

These surfaces are also 1-isospectral to each of four hyperbolic surfaces with boundary having 2, 4, $2g - 2$, and $2g$ boundary components, respectively.
We remark that (b) implies (c), since the 0-spectrum determines the weak length spectrum (i.e., the spectrum of lengths of closed geodesics, ignoring multiplicities) in the case of hyperbolic manifolds. (Aside: For Riemann surfaces, it is a classical result of Huber that the 0-spectrum and the strong length spectrum, i.e., the spectrum of lengths, counting multiplicities, determine each other. This result has been extended to non-orientable hyperbolic surfaces by Peter Doyle and the second author in an article in preparation.)

![Diagram of a right-angled hexagon and a pair of pants.](image)

**Figure 1.** Right-angled hexagon and the associated pair of pants.

**Proof.** We construct an orientable surface $S$ as follows: Let $Y$ be a pair of hyperbolic pants, as shown in Figure 1; the boundary geodesics of the pant legs have the same length, while the waist may have a different length. The pants are formed by gluing together two identical right-angled geodesic hexagons along three sides. The hexagon is also pictured in Figure 1. Choose a positive integer $t$ and glue together $4t$ isometric copies $Y_1, \ldots, Y_{4t}$ of $Y$ to obtain a Riemann surface $S$ of genus $2t + 1$. To describe the symmetries, we will visualize $S$ (as shown in Figure 2 in case $t = 1$) as obtained from a surface $N$ with boundary in $\mathbb{R}^3$ with appropriate identifications of boundary edges. The three symmetries $\tau_H$, $\tau_V$, and $\tau_P$ of $N$ given by reflection across the $xy$-plane, the $xz$-plane and the $yz$-plane, respectively, define commuting involutive isometries of $S$. (We are using the indices $H$, $V$, and $P$ here to indicate reflection across planes that are horizontal, vertical, or the plane of the paper.) There are additional isometric involutions of $S$ (not of $N$) given by reflections across vertical planes passing through the waists of two of the pants. Choose such a symmetry and denote it by $\tau_{V_2}$. E.g., in case $t = 1$, a choice of $\tau_{V_2}$ interchanges pants $Y_1$ with $Y_2$ and $Y_3$ with $Y_4$ in Figure 2. Finally, let $\rho$ be the orientation preserving isometric involution (rotation) $\rho$ sending the pair of pants $Y_i$ to the pants $Y_{i+2t}$ mod $4t$, for each $i$. Note that $\tau_H$ and $\tau_P$ commute with $\rho$. Thus the isometries $\tau_1 := \tau_H \circ \tau_V \circ \tau_P$, $\tau_2 := \tau_P \circ \rho$, $\tau_3 := \tau_H \circ \rho$, and
\(\tau_4 := \tau_H \circ \tau_{V_2} \circ \tau_P\) are involutive, orientation-reversing, fixed-point-free isometries of \(S\). We set \(S_i = \langle \tau_i \rangle \backslash S\), for \(i = 1, 2, 3, 4\). The surfaces \(S_i\) are depicted in Figure 3 in case \(t = 1\). These non-orientable surfaces have genus \(g = t + 1\), and, topologically, they are spheres with \(t - 1\) handles and two cross handles, or equivalently, spheres with \(t + 1\) cross handles.

![Figure 2. Four congruent pants glued to form \(S\).](image)

For generic choices of the hyperbolic pants \(Y\) used to build the surfaces above, the four surfaces will have different geodesic length spectra. For concreteness, we will make a specific choice of \(Y\) to guarantee that one of the surfaces has a strictly smaller injectivity radius than the others. There exists a unique right-angled hexagon as in Figure 1 for each given choice of \(\alpha\) and \(\gamma\). (See Buser [B], Theorem 2.4.2.) We choose \(\alpha\) and \(\gamma\) to be less than \(\text{arcsinh}(1)\) and to satisfy \(\gamma < 2\alpha\). Since the waist of the resulting pants has length \(2\gamma\) and the boundary geodesics of the legs have length \(2\alpha\), the resulting surface \(S\) has \(2t\) closed geodesics of length \(2\gamma\) and \(4t\) of length \(2\alpha\). By Theorem 4.1.6 of [B], a surface of genus \(g\) can have at most \(3g - 3\) simple closed geodesics of length less than or equal to \(2\text{arcsinh}(1)\). Thus the geodesics in \(S\) corresponding to the boundary geodesics of the pants are the only simple closed geodesics satisfying this bound on their lengths.

Now for \(i = 1, 2, 3, 4\), consider the shortest “new” closed geodesic in the surface \(S_i\), i.e., the shortest closed geodesic that does not lift to a closed geodesic of the same length in \(\tilde{S}\). These geodesics are depicted in Figure 3 in case \(t = 1\). (The relative lengths of the geodesics in the figures are distorted.) The surface \(S_4\) contains a geodesic of length \(\gamma\). This geodesic is shorter than any closed geodesic in the other surfaces. Thus \(S_4\) has smaller injectivity radius than the others. Thus statement (b) of the Theorem is satisfied.
Figure 3. The non-orientable surfaces $S_i$; the shortest “new” geodesics are thicker.

For the final statement of the theorem, we use Corollary 1.4 to observe that the surfaces $S_i$ are also 1-isospectral to the four surfaces $\langle \tau_P \rangle \backslash S$, $\langle \tau_H \rangle \backslash S$, $\langle \tau_V \rangle \backslash S$, and $\langle \tau_V \rangle \backslash S$ with boundary. These surfaces have $2g$, $2g - 2$, 4 and 2 boundary components, respectively.

2.9. Remark. Letting $S$ be the surface of genus $2n$, $n \geq 1$, pictured in Figure 4, one may take the quotient of $S$ by each of the three visual symmetries (reflection across a vertical plane, horizontal plane, and plane of the paper) to obtain 1-isospectral surfaces with boundary. The first has only one boundary component, while the others have $2n + 1$.

Figure 4. A Riemann surface and a reflection plane.

2.10. Surfaces with boundaries of arbitrarily different shapes. This final example involves manifolds of mixed curvature. Let $M$ be a 2-sphere with a non-standard metric, symmetric with respect to reflection across two orthogonal planes. The quotients of $M$ by these isometric involutions are 1-isospectral manifolds with boundaries. By
choosing the metrics on $M$ appropriately, one can more or less arbitrarily prescribe independently the geodesic curvatures of the boundary curves.

3. Examples of orbifolds and manifolds isospectral in the middle degree

Does the spectrum distinguish orbifolds with singularities from smooth manifolds? We will see below that the middle degree Hodge spectrum cannot detect the presence of singularities. We do not know whether the 0-spectrum always detects singularities. However, we will show in Propositions 3.4 and 3.5 that it does in many situations, including all the examples we will give of orbifolds and manifolds which are isospectral in the middle degree.

3.1. Theorem. (Corrected version of Theorem 3.1 in the original paper.) The 1-spectra of the cylinder, Klein bottle and Möbius strip of Example 2.5 agree with that of a four pillow $O$ except for the presence of the eigenvalue zero in the former.

Proof. The four pillow is the quotient of $T = \mathbb{Z}^2 \setminus \mathbb{R}^2$ by the involution $\rho$ induced from the map $-Id : \mathbb{R}^2 \to \mathbb{R}^2$. It is a pillow-shaped orbifold with isolated singularities at the four corners. Since $\rho$ is not orientation reversing, we cannot apply Corollary 1.4. Instead we will compare the spectra directly.

Every 1-form on $T$ may be written in the form $fdx + gdy$, where $dx$ and $dy$ are the forms induced on $T$ by the standard forms on $\mathbb{R}^2$. Since

$$\Delta(f dx + gdy) = \Delta(f) dx + \Delta(g) dy,$$

spec$_1(T)$ consists of two copies of spec$_0(T)$. Hence each of the manifolds in Example 2.5 has 1-spectrum equal to the 0-spectrum of $T$.

Since both $dx$ and $dy$ are $\rho$-anti-invariant, the space of $\rho$-invariant one-forms on $T$ is given by

$$\{f dx + gdy : \tau^*f = -f, \tau^*g = -g\}.$$

Thus spec$_1(O)$ is formed by two copies of the spectrum of the Laplacian of $T$ acting on the space of $\rho$-anti-invariant smooth functions. By Fourier decomposition on the torus, one sees that the Laplacian of $T$ restricted to the $\rho$-anti-invariant smooth functions has the same spectrum as the Laplacian restricted to the $\rho$-invariant smooth functions except for the presence of zero in the latter. The proposition follows. \qed
3.2. **Theorem.** (i) For each positive integer \( m > 1 \), there exists a collection of \( m - 1 \) distinct mutually \( m \)-isospectral \( 2m \)-dimensional flat orbifolds having singular sets of dimension \( 1, 3, 5, \ldots, 2m - 3 \), respectively. Moreover, these orbifolds are also \( m \)-isospectral to the direct product of a cubical \((2m - 2)\)-torus with each of the manifolds of Example 2.5.

(ii) For each positive integer \( m > 1 \), there exists a collection of \( m - 1 \) distinct mutually \( m \)-isospectral \( 2m \)-dimensional spherical orbifolds having singular sets of dimension \( 1, 3, \ldots, 2m - 3 \), respectively. Moreover, these orbifolds are also \( m \)-isospectral to a \( 2m \)-dimensional projective space and to a \( 2m \)-dimensional hemisphere.

**Proof.** (i) For \( k \) odd with \( 1 \leq k \leq 2m - 3 \), let \( \tau_k \) be the orthogonal involution of \( \mathbb{R}^{2m} \) given by the \( 2m \times 2m \) diagonal matrix \( \text{diag}(-1, \ldots, -1, 1, 1, \ldots, 1) \). Then \( \tau_k \) induces an orientation reversing involution, which we also denote by \( \tau_k \), of the \( 2m \)-dimensional cubical flat torus \( T \). Let \( O_k \) be the quotient of \( T \) by \( \tau_k \). By Corollary 1.4, these orbifolds are mutually \( m \)-isospectral. Since the direct product of a cubical \((2m - 2)\)-torus with any of the manifolds or orbifolds in Theorem 3.1 may also be viewed as a quotient of \( T \) by an involution, the final statement of the theorem follows. (Aside: One could also take \( k = 2m - 1 \) to obtain an orbifold with singular set of dimension \( 2m - 1 \). However, under the identification described in Remark 1.2(iii), this orbifold is identified with the product of the cylinder in Theorem 3.1 with the cubical torus and thus is redundant.)

(ii) We now let \( \tau_k \), for \( k \) even with \( 2 \leq k \leq 2m - 2 \), be the orthogonal involution of \( \mathbb{R}^{2m+1} \) given by the \( (2m + 1) \times (2m + 1) \) diagonal matrix \( \text{diag}(-1, \ldots, -1, 1, 1, \ldots, 1) \). The quotient of the \( 2m \)-sphere by \( \tau_k \) is an orbifold with singular set of dimension \( k - 1 \). Again by Corollary 1.4, these orbifolds are mutually \( m \)-isospectral and are also \( m \)-isospectral to the projective space and hemisphere of Example 2.2. (Aside: If we take \( k = 2m \), we obtain the hemisphere under the identification in 1.2.)

**Remark.** One can enlarge the collection of manifolds and orbifolds that are \( m \)-isospectral to those in Theorem 3.2(i) by taking the quotient of \( \mathbb{Z}^{2m} \backslash \mathbb{R}^{2m} \) by any of the involutions \( \tau_k \circ L_b \), where \( \tau_k \) is defined as in the proof of the theorem and \( L_b \) is translation by an element of \( (\frac{1}{2}\mathbb{Z})^{2m} \) not in \( \mathbb{Z}^{2m} \).

In [MR1], [MR2], R. Miatello and the second author computed all the various \( p \)-spectra of flat manifolds. Their method extends to flat
orbifolds and can be used to give an alternative proof of Theorem 3.2(i) as well as of the earlier examples of flat manifolds and/or orbifolds.

We next show that the orbifolds and manifolds in Theorems 3.1 and 3.2 are not 0-isospectral. The orbifolds in these examples belong to the class of so-called “good” Riemannian orbifolds; that is, they are quotients of Riemannian manifolds by discrete, effective, properly discontinuous isometric group actions.

3.3. Lemma. \[ D1, D2 \] Let \( O \) be a good closed Riemannian orbifold, and let \( \lambda_1, \lambda_2, \ldots \) be the 0-spectrum of the Laplacian. Then there is an asymptotic expansion as \( t \downarrow 0 \) of the form

\[
\sum_{i=1}^{\infty} e^{-\lambda_i t} \sim (4\pi t)^{-\frac{n}{2}} \sum_{k=0}^{\infty} a_k t^k + \sum_S B_S(t),
\]

where \( S \) varies over the primary strata of the singular set and where \( B_S(t) \) is of the form

\[
B_S(t) = (4\pi t)^{-\frac{\dim(S)}{2}} \sum_{k=0}^{\infty} b_{k,S} t^k
\]

with \( b_{0,S} \neq 0 \). The coefficients \( a_k \) in the first part of the expansion are given by the same curvature integrals as in the heat expansion for manifolds; in particular, \( a_0 =\text{vol}(O) \).

Remarks. (i) There is an apparent typographical error in the statement of this result as Theorem 4.8 in the article \[ D2 \] in that the power \( (4\pi t)^{-\frac{\dim(S)}{2}} \) is missing. However, the proof makes the expression clear.

(ii) Donnelly did not state his result in terms of the strata of the singular set. Instead, writing \( O = \Gamma \setminus M \), where \( M \) is a Riemannian manifold and \( \Gamma \) is a discrete group of isometries acting properly discontinuously, he computed the contributions to the heat invariants arising from the fixed point set \( \text{Fix}(\gamma) \) of each element \( \gamma \in \Gamma \). The formulation in Lemma 3.3 is obtained by collating these contributions. The lemma and also Proposition 3.4(i) were generalized to all closed Riemannian orbifolds in \[ DGGW \]. Later Naveed Bari pointed out an error in the statement that \( b_{0,S} \neq 0 \) for every singular stratum. This error was corrected in \[ DGGW2 \] by adding the word “primary”. In the setting of good orbifolds, a stratum \( S \) is primary if there exists at least one element \( \gamma \in \Gamma \) such that \( \Gamma \) is open in \( \text{Fix}(\gamma) \). For more details and an example of a non-primary stratum, see \[ DGGW2 \].

3.4. Proposition. Let \( O \) be a good Riemannian orbifold with singularities. Then:

(i) If \( O \) is even-dimensional (respectively, odd-dimensional) and some primary stratum of the singular set is odd-dimensional (respectively, even-dimensional), then \( O \) cannot be 0-isospectral to a Riemannian manifold.
(ii) If $N$ is a manifold such that $\mathcal{O}$ and $N$ have a common finite Riemannian cover, then $N$ and $\mathcal{O}$ are not 0-isospectral.

**Proof.** (i) In the two cases, the fact that $\mathcal{O}$ is an orbifold can be gleaned from the presence of half-integer powers, respectively integer powers, of $t$ in the asymptotic expansion in Lemma 3.3. (ii) Suppose $N$ and $\mathcal{O}$ have a common finite covering $M$. By Lemma 3.3, the spectrum of $\mathcal{O}$ determines its volume and thus the degree $d$ of the covering $M$ is the same for $\mathcal{O}$ and $N$. The first part of the heat expansion (the part involving the $a_k's$) is the same for $\mathcal{O}$ and $N$ since $a_k(\mathcal{O}) = \frac{1}{d}a_k(M) = a_k(N)$. The second part of the expansion vanishes for $N$ but not for $\mathcal{O}$. Hence the trace of the heat kernels of $N$ and $\mathcal{O}$ have different asymptotic expansions, so $N$ and $\mathcal{O}$ can’t be 0-isospectral. □

**3.5. Remark.** Craig Sutton [Sut2] later generalized Proposition 3.4(i). Instead of assuming that $\mathcal{O}$ and $N$ have a common finite Riemannian cover, he assumed only that some finite Riemannian cover of $\mathcal{O}$ is isospectral to a finite Riemannian cover of $N$.

Statement (i) remains valid without the assumption that the cover is a finite cover (equivalently that $M$ is compact) provided that $M$ is a Riemannian homogeneous space. Indeed, in this case, for each $k$ the curvature expressions $u_k$ whose integrals yield the heat invariants $a_k$ are constants that depend only on the geometry of $M$, and we have $a_k(\mathcal{O}) = \text{vol}(\mathcal{O})u_k = \text{vol}(N)u_k = a_k(N)$. The rest of the argument above goes through.

**3.6. Proposition.** None of the manifolds and orbifolds in Theorems 3.1 and 3.2 are 0-isospectral.

**Proof.** By Proposition 3.4(ii), the closed manifolds in these theorems are not 0-isospectral to the orbifolds. As discussed in Remark 1.2, the manifolds with boundary in these theorems are the underlying spaces of (closed) orbifolds; the boundaries of the manifolds form the singular sets of the orbifolds. Moreover the Neumann spectrum of each such manifold coincides with the 0-spectrum of the associated orbifold. Thus we are reduced to comparing the 0-spectra of various orbifolds, each of which has a singular set consisting of a single strata. Moreover, the orbifolds in each collection have the same constant curvature and have a common covering as orbifolds. In particular, the first part of the heat expansion in Lemma 3.3 is identical for the various orbifolds. However, since their singular strata have different dimensions, the second part of the expansion differs. Thus they cannot be 0-isospectral. □
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